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TECHNICAL NOTE

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RANGE OF INTERFACE THERMAL CONDUCTANCE FOR AIRCRAFT JOINTS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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TECHNICAL NOTE D-426

RANGE OF INTERFACE THERMAL CONDUCTANCE FOR AIRCRAFT JOINTS

By Martin E. Barzelay

SUMMARY

As an extension of previous experimental investigations more than 100 aluminum-alloy and high-temperature-alloy structural-joint specimens consisting of a stringer joined to a skin surface were tested under simulated aerodynamic heating conditions. Interface thermal conductance was determined from transient temperature records.

Most of the specimens were made geometrically identical and of the same aluminum alloy in order to take into account manufacturing variability (including interface cleanliness condition) and the effect of many different types of fastenings (including those whose torque was varied as part of the investigation). In addition, other specimens were designed to account for changes in skin thickness, for the use of sandwich materials at the interface, and for different materials in skin and stringer.

The heat input was nearly constant during any given test at values which ranged from approximately 3,500 to 140,000 Btu/(sq ft)(hr). Mean interface temperatures as high as 600° F were achieved during the transient heating. Tests lasted up to 5 minutes in some cases, but most of the tests were conducted during a period of less than 1 minute. In testing the effect of heating history the shortest interval between tests was 15 minutes and the longest was 104 days.

Interface-conductance values ranged from approximately 80 to 2,150 Btu/(sq ft)(hr)(°F).

The interface conductance showed a considerable range of variability for seemingly identical specimens even when specimens were manufactured under controlled laboratory conditions. The rate of heat flow into the specimen had a major effect on interface conductance as did the type of connection used for fastening the skin to the stringer. The interface conductance was found to be independent of heating history as defined by the length of time between tests.

INTRODUCTION

The previous experimental investigations of references 1 to 4 demonstrate that the value of thermal conductance across a joint interface involves many material and manufacturing variables which form complicated, even if determinate, relationships. Thus realistic and practically applicable interface-conductance values must be found from experiments on actual joint samples.

It has been recognized for some time that joint thermal conductivity can have an important effect on temperature and thermal stresses in aerodynamically heated aircraft structures. The work of reference 5, for example, points out some of these effects. In their introduction the authors say: "Transient thermal stresses produced by aerodynamic heating of supersonic aircraft may result in buckling, warping, flutter, loss of stiffness, or other deleterious effects which might seriously penalize the performance of the aircraft. In order for the designer to eliminate or minimize these effects, he must know how the thermal stresses are affected by such factors as flight conditions, materials, and the presence of structural discontinuities such as joints. At present, little information is available concerning the effects of joint conductivity on the thermal stresses; such information is needed for the alleviation of these thermal stresses and their accompanying undesirable effects."

More recently attention has been focused on interface conductance by reference 6. It was concluded by the authors that ". . . normal fabrication techniques can produce joints of such poor conductivity as to cause the temperature differences to increase markedly over those of an integral structure." Even more startling was the dynamic failure of a test wing, apparently due to the adverse effect of joint conductivity. One need not labor the point further that joint conductivity must be given attention as a major parameter in the design of heated aircraft structures.

Early efforts in the field of interface conductance were directed toward finding the effects of basic parameters such as surface roughness, temperature, and pressure on a simple clearly defined interface. These early efforts were then extended to provide realistic and practical values for some of the more commonly used types of aircraft joints, taking into account factors such as rivet diameter and pitch, skin thickness, and geometry. Pertinent data are given in the listed references.

In order to extend these efforts further the present report presents interface-conductance data for a common type of skin-stringer construction under a range of conditions of the interface (including sandwiches), with many types of connections and for several skin thicknesses. The effects of heating history and of rate of heating are a part of the presentation.

Most important, a study is made of the effect of manufacturing variability on interface conductance, that is, a study of the range of variability of seemingly identical joints which can lead to failures of the type alluded to above.

Test specimens were supplied by Bell Aircraft Corp., Glenn L. Martin Co., Northrop Aircraft, Inc., and Republic Aviation Corp. to encompass as wide a range as possible of manufacturing techniques, types of materials, and connections; also, some specimens were manufactured at Syracuse University. This investigation at Syracuse University was sponsored by and conducted with the financial assistance of the National Advisory Committee for Aeronautics.

The author wishes to thank Mr. John W. Schaefer, Mr. Andrejs Saule, and Mr. Peter Gazzara for their assistance in the test program.

SYMBOLS

A	cross-sectional area of stringer, sq in.
c	specific heat, Btu/(lb)($^{\circ}$F)
e	distance to rivet center line, in.
h	interface thermal conductance, Btu/(sq ft)(hr)($^{\circ}$F)
h_i	interface thermal conductance parameter for sandwich material, $\frac{ht_i}{k_i}$
k	conductivity, Btu/(hr)(ft)($^{\circ}$F)
k_i	conductivity of interface sandwich material, Btu/(hr)(ft)($^{\circ}$F)
l_f	length of flange in cross section, in.
l_w	length of web in cross section, in.
P	rivet pitch, in.

Q	heat flow into specimen, Btu/(sq ft)(hr)
q	heat flow across interface, Btu/(sq ft)(hr)
T	temperature, $^{\circ}F$
T_m	mean interface temperature, $^{\circ}F$
ΔT	temperature drop across interface, $^{\circ}F$
t_a	thickness of flange, in.
t_i	thickness of interface sandwich material, in.
t_s	skin thickness, in.
w	specific weight, lb/cu ft
θ	time, sec
ϕ	dimensionless mean temperature parameter, $T_m \frac{k}{qt_s}$
ϕ_i	dimensionless mean temperature parameter, $T_m \frac{k_i}{qt_i}$

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DESCRIPTION OF TEST APPARATUS

A general view and a closeup view of the test apparatus are shown in figures 1 and 2. The heating bank consisted of 24 parallel General Electric No. 1000T3 quartz lamps on 1/2-inch centers with a radiating area of 10 by 12 inches. The heating bank could readily be connected to a 480- or 240-volt supply in either a Y- or delta connection, affording considerable flexibility of power input and thus flexibility of heating rate at the specimen. An air-cooled polished-aluminum reflector was placed behind the heating bank to minimize losses. Air-cooling was also provided for the specimen to reduce the time between test runs.

The specimen was mounted in a movable frame by simple supports at the four corners. The distance between the heated skin surface and the heating bank was held at 2 inches for most of the tests but could be readily varied if desired.

A Century, Model 408, multichannel recording oscillograph recorded directly all thermocouple outputs. All of the galvanometers in the oscillograph had a nominal sensitivity of 12 microamperes per inch of deflection on the recording paper. The specially designed calibrator described in reference 3 was utilized in the thermocouple circuits. The function of the calibrator was to take into account the total resistance of each matched thermocouple-galvanometer loop and to adjust the galvanometer sensitivity, with the aid of a variable-series resistor, so that a given voltage signal from the thermocouple (i.e., a given temperature) corresponded to any desired trace deflection. All channels could be calibrated in a minimum time before each test.

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TEST PROCEDURE

Theoretical Basis and Testing Technique

The theoretical basis for the type of tests conducted was outlined in reference 3 and discussed at greater length in reference 4. The method of calculating interface conductance as outlined in appendix A of reference 3 was somewhat modified in the section "Evaluation of Data" in reference 4. A further modification was utilized in making calculations for this report.

As before, with the two basic variables ΔT and $\partial T/\partial \theta$ determined from the test, the interface conductance can be found from the relationship

$$h = \frac{q}{\Delta T} = \frac{cwA \dfrac{\partial T}{\partial \theta}}{l_f \Delta T}$$

where c and w are, respectively, the specific heat and specific weight of the stringer downstream of the interface, A is the cross-sectional area of this stringer, and l_f is the length of contact in the cross section.

The calculations for interface conductance are thus based on the heat flow q across the interface as determined from conditions in the structure downstream, that is, at the cross section of the skin-stringer specimen where temperature measurements are made. However, for each test run a heat flow Q was also calculated from the rate of temperature increase at a point 3 inches from the center line of the rivets. It is the average value of this heat flow Q which is given as a reference value in the tables and graphs of this report.

Also in this report the specific heat, previously assumed to be a constant, is treated as a variable function of the average temperature in the stringer for calculating q, or of the average temperature in the skin for calculating Q. Further refinements are made in the calculation procedure by weighting the three individual ΔT values at the interface in accordance with their position; that is, the ΔT value for the position under the stringer leg is given less weight since the outstanding leg influences the temperature drop by acting as a heat sink. As before, corrections were made for the small temperature drop over the distance between the thermocouples and the interface.

The changeover in the test apparatus from graphite rods to quartz heating rods does not materially change the considerations of references 3 and 4. One qualification, however, should be made; that is, on the basis of the more recent experimental evidence of this report, it is no longer felt that stress distribution has a negligible effect on the interface conductance. While for most situations the assumption of negligible stress distribution still appears to hold, it is believed that only warping of the specimen caused by stresses can account for some of the observed effects of the heat-flow rate and may account for some of the otherwise unexplained variation in interface-conductance values found in seemingly identical tests on identical specimens.

Description of Specimens

The general configuration of the test specimens was a 10- by 10-inch skin surface with an extruded or bent-up angle riveted or otherwise attached according to standard aircraft practice along one center line as described in figure 3 and table I. Table I(a) describes the specimens as to configuration, material, and interface condition (including sandwich materials as an interface condition), and table I(b) describes the same specimens as to the type of connection used between skin and stringer.

Specimen materials consisted of 2024-T and 2024-T3 aluminum alloy, 6Al-4V titanium alloy, 17-7 PH stainless steel, and Inconel X. Most specimens were fabricated with the skin and angle of the same material; however, some combinations of the above materials were also fabricated for the test program.

The interface joint in most specimens was clean and bare; however, in some specimens it was deliberately made dirty, painted with zinc-chromate primer or contained a sandwich of aluminum sheet, brass shimstock, sheet asbestos, or Teflon sheet.

The basic type of connection used in the test program was the 3/16-inch-diameter, solid 2024-T aluminum-alloy rivet with

100^{o} countersunk head, known by the designation AN426-DD. When the type of connection was under investigation or the pressure was to be varied, other types of connection were used. These other types used in the fabrication of specimens included tubular and Cherry rivets, Hi-Shear pins, lockbolts, screws and nuts, and spotwelds. The bulk of the specimens had a skin thickness of 0.156 inch, but some had 0.313-inch-thick skin.

As a part of the program two groups of specimens were prepared to investigate the variability of seemingly identical joints. In the first group 20 specimens were fabricated by three aircraft manufacturers. It was requested that normal fabrication techniques be employed, though no guarantee can be given that this instruction was carried out since special orders in an aircraft factory are frequently handled in the experimental shop in a more careful way than ordinary. In the second group 12 specimens geometrically identical to those of the previous group were fabricated at Syracuse University, nine of which were selected for testing. The interface surfaces were carefully machined and checked for both flatness and surface roughness. The fastenings consisted of screws and nuts in order that the interface pressure could be carefully controlled by measuring the torque applied to the nuts. Extreme care was taken in handling these specimens during their fabrication to avoid scratching or contaminating the mating interfaces in any way.

The test program for the nine identical specimens was carried out in such a manner that information over and above the aforementioned manufacturing variability could be secured. The effect of heating history on the interface conductance was introduced by selecting a different time interval for testing each of the nine specimens. In addition, several of the nine specimens were subsequently used for tests where heat flow was the controlled variable and where pressure at the interface was controlled by means of tightening the connection.

Thermocouple Technique

The thermocouple technique followed the practice of previous investigations reported in references 3 and 4.

For many of the specimens two cross sections A and B were investigated with the thermocouples located as shown in figure 4. In presenting the data the interface-conductance values at cross section B, which was close to the rivets, were not used except for orientation purposes and in all later tests the thermocouples for this location were omitted.

Conduct of Tests

Each specimen was subjected to a number of short-duration transient heating runs; with a few exceptions the minimum number of runs for any specimen was two and some specimens were tested as many as 25 times.

Before a test run was begun each thermocouple-galvanometer pair was individually calibrated.

In the course of a test the intensity of the heating lamps reached
a maximum in less than 1 second after the power was turned on and W
remained constant during the test run. The voltage, which determined 1
the lamp intensity and thus the heating rate after the warmup period of 3
less than a second, could be varied from test to test by changing the 9
electrical connections, but no voltage control was provided during a test run.

The output of all thermocouples was simultaneously recorded during a test and a permanent record was thus available for later evaluation.

The heat input was nearly constant during any test at values ranging from approximately 3,500 Btu/(sq ft)(hr) to 140,000 Btu/(sq ft)(hr). Mean interface temperatures as high as 600° F were achieved in tests which lasted up to 5 minutes in some cases, although the duration of most was less than 1 minute.

Tests were run at various time intervals during the investigation. In testing the effect of heating history the shortest interval between tests was 15 minutes and the longest was 104 days.

PRECISION OF DATA

The subject of precision of the data was discussed at considerable length in references 3 and 4 as it pertained to the precision of the interface-conductance data. Since the work of those references, several modifications have been made in testing technique and the methods of evaluating data which warrant comment.

In reference 3 some attention was devoted to the ability to attain prescribed boundary conditions. At that time the use of graphite rods as a source of radiant heat contributed to the nonuniformity of heat flow. In the current investigation the use of quartz rods as heating elements largely eliminated localized heating effects.

The assumption of perfect insulation over the unheated surfaces was further substantiated by tests of typical specimens with an insulated backing of 3 inches of diatomaceous earth. On the basis of these tests it was decided that corrections for heat losses were not warranted in calculating interface conductance from the recorded data.

The refinements of calculating technique outlined in the section "Test Procedure" are believed to lead to greater accuracy in the final interface-conductance values than hitherto attained.

The values of interface conductance presented herein are estimated to be correct to within ±8 percent.

RESULTS AND DISCUSSION

The interface conductance was determined experimentally for the more than 100 aluminum-alloy and high-temperature-alloy structural-joint specimens previously described in this report.

Most of the specimens were made geometrically identical and of the same aluminum alloy in order to take into account manufacturing variability (including interface cleanliness condition) and the effect of many different types of fastenings (including those whose torque could be varied as part of the investigation). In addition other specimens were designed to account for changes in skin thickness, for the use of sandwich materials at the interface, and for different materials in skin and stringer.

The interface-conductance values measured in the entire program ranged from approximately 80 Btu/(sq ft)(hr)($^{\circ}$F) to 2,150 Btu/(sq ft)(hr)($^{\circ}$F).

The data for each test run consisted of temperature-time oscillograph records for 18 selected points in the specimen, 10 points at the midrivet cross section, and 8 points at the near-rivet cross section. The interface-conductance values derived from these data are presented in the form of graphs and tables. In each case where data have been averaged the number of tests represented is noted.

In processing the data the usual procedure was to calculate the interface conductance and the corresponding mean interface temperature at four equal time intervals for any given test. In order to compare the interface-conductance values from a number of specimens on some common basis, linear interpolation was utilized to find the interface conductance at equal intervals of mean interface temperature.

Manufacturing Variability

The effect of manufacturing variability on interface conductance was studied first with a group of 20 specimens fabricated by three manufacturers. Twelve of these were geometrically identical but varied as to the interface condition and as to manufacturer. Eight additional specimens were fabricated which differed from the original twelve in that their skin thickness was increased from 0.156 to 0.313 inch. These eight were identical geometrically with each other (and with the group of twelve except for skin thickness) and all had bare and clean interfaces.

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Details of the above specimen fabrication are given in table I, but the grouping below should help to clarify the presentation of results which follows. The first letters of the code numbers indicate the differing manufacturers of the specimens.

Interface condition	Twelve specimens t_s = 0.156 inch	Eight specimens t_s = 0.313 inch
Bare, clean	M-1-A M-1-B R-1-A R-1-B R-1-C R-1-D	M-3-A M-3-B N-3-A N-3-B R-2-A R-2-B R-2-C R-2-D
Bare, dirty	M-2-A M-2-B	-----
Zinc chromate, clean	N-1-A N-1-B	-----
Zinc chromate, dirty	N-2-A N-2-B	-----

In figure 5(a), the six identical specimens with bare and clean interfaces are compared. These six were fabricated as shown in figure 3(a) by two different manufacturers. All of the tests were conducted at approximately the same heat flow, which therefore does not appear as a variable, to determine the interface conductance at various mean interface temperatures. Four of the six specimens were tested a large number of times to ascertain average values as indicated in the figure.

As may be seen in figure 5(a), there was a considerable variability of interface conductance from specimen to specimen at the same mean interface temperatures. The highest average value of interface conductance for all six specimens was 1,069 Btu/(sq ft)(hr)($^{\circ}$F) at $T_m = 100^{\circ}$ F and the lowest was 330 Btu/(sq ft)(hr)($^{\circ}$F) at $T_m = 400^{\circ}$ F, indicating a difference of about 3.5 to 1. Even at the same mean temperature of 100° F, differences in interface conductance of almost 2.5 to 1 are apparent.

It should also be reported that in computing the averages for specimen M-1-B, which are plotted in figure 5(a), the individual tests were noted to have a greater range when compared with each other at the same mean interface temperatures than was apparent in the other tests plotted in this figure. The highest and lowest values for all of the tests on specimen M-1-B were omitted from the averages but are reported here because of their indication of the possible extreme range of values which can be expected. The highest value was 1,611 Btu/(sq ft)(hr)($^{\circ}$F) at $T_m = 100^{\circ}$ F and the lowest, 394 Btu/(sq ft)(hr)($^{\circ}$F) at $T_m = 400^{\circ}$ F, but for two different tests. Thus for a single specimen there is a possible range of over 4 to 1 in interface conductance over the mean interface temperature range of 100° to 400° F. As an indication of scatter this same high value of 1,611 Btu/(sq ft)(hr)($^{\circ}$F) may also be compared with the lowest value at the same mean interface temperature of 100° F which was 819 Btu/(sq ft)(hr)($^{\circ}$F).

In figure 5(b) four identical specimens are compared which were fabricated as shown in figure 3(a) by the same manufacturer. The geometry is the same as that for the six specimens in figure 5(a), but in this case the interface has been painted with zinc-chromate primer, and two of the specimens have been assembled in a dirty condition. The degree of "dirtiness" is rather hard to define; it may range from greasy finger prints to chips in the interface.

One of the specimens, N-1-A, was tested repeatedly and the points plotted in figure 5(b) represent averages derived from 26 tests. In all of the tests there appears to be little if any change of interface conductance with mean interface temperature, contrary to the trend of figure 5(a) where the interface conductance of the bare and clean specimens decreased with mean interface temperature. The interface-conductance values appear to change little from specimen to specimen for three of the specimens, all values lying between approximately 250 and 350 Btu/(sq ft)(hr)($^{\circ}$F); the fourth specimen, N-1-B, gave values approximately 40 percent higher than the highest of the three.

The average heat flow for the 26 tests on specimen N-1-A ranged from 13,000 to 50,000 Btu/(sq ft)(hr) while those for the three remaining specimens ranged from 32,000 to 38,000 Btu/(sq ft)(hr), but no discernible effect of heat flow could be determined in comparing individual tests. Therefore, heat flow is not included as a parameter. One specimen, N-2-A, was singled out for another series of tests to determine heat flow effects and the results are reported in the following discussion.

The effect of heat-flow rate on interface conductance for specimen N-2-A is shown in figure 5(c) at values of mean interface temperature of up to 600° F. For this type of specimen, that is, one with a zinc-chromate primer and the interface in a dirty condition, no significant effect of heat-flow rate nor any trend in the data with heat-flow W
rate was apparent. In fact, the interface-conductance values for flow 1
rates of 140,000 Btu/(sq ft)(hr) are seen to lie between those for 15,000 3
and 11,000 Btu/(sq ft)(hr), with a flow rate of 54,000 Btu/(sq ft)(hr) 9
giving the highest values for this sequence of tests. This lack of significant difference or trend of the data with heat flow is contrary to data which will be reported later in this section for a specimen geometrically similar to N-2-A, but one in which the interface was clean and the interface pressure carefully controlled from test to test.

Eight geometrically identical specimens with clean, bare interfaces which were fabricated by three different manufacturers are compared in figure 5(d). Fabrication was as shown in figure 3(a) with a skin thickness of 0.313 inch compared with 0.156 inch for the previously discussed specimens. Again there appears to be a considerable difference in properties among specimens fabricated by different manufacturers as in figure 5(a), but since there is also a difference in the heat-flow rate between the specimens from the three manufacturers, the interface-conductance data were replotted in figure 5(e) against the dimensionless mean temperature parameter ϕ instead of T_m. The difference in specimens with regard to interface-conductance values is still seen to be significant, but the slopes of the curves are more nearly alike than in figure 5(d). Specimen R-2-C was omitted for clarity in replotting the data in figure 5(e).

In figure 5(f) the interface-conductance data for four specimens (M-1-A, M-1-B, M-3-A, and M-3-B) are replotted from figures 5(a) and 5(d) to show the effect of change in skin thickness. The four specimens were all fabricated by the same manufacturer and were tested at approximately the same heat flow. It would appear that individual differences are sufficiently great to obscure the effect of skin thickness on interface conductance, but the tendency of thinner skins to give higher interface-conductance values, as indicated by the large number of tests shown in figure 6 of reference 4, is somewhat borne out by this figure. In view of what has been said previously in this report concerning the effect of differences in interface conductance for seemingly identical configurations, it is considered of some importance that such differences as indicated by specimens M-1-A and M-1-B be kept in mind when referring to figure 6 of reference 4.

The effect of cleanliness at the interface on the interface conductance is shown in figure 5(g) for four identical specimens with bare interfaces fabricated by the same manufacturer. Although the average curve for the two clean-interface specimens is seen to be somewhat higher than that for the two dirty-interface specimens, the overlap is seen to be such that, when the results for all four specimens are plotted, no significant difference can be attributed to the cleanliness effect in this case. In fact the lower of the two curves for clean specimens falls below the lower of the two curves for dirty specimens at mean interface temperatures above about 200° F. It might also be noted that this behavior is contrary to that exhibited in the case of the clean and dirty specimens of figure 5(b) which were painted with zinc-chromate primer.

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Sandwich Materials

Six specimens of the same geometrical configuration as that shown in figure 3(a) were tested with various sandwich materials at the interface. All were fabricated by the same manufacturer. The results are shown in figure 6(a) where the average interface conductance for two tests for each specimen are plotted against mean interface temperature. As might be expected the good conductors such as aluminum and brass gave conductance values which were better than those for the asbestos, but it is interesting to note that the 0.010-inch-aluminum sandwich gave interface-conductance values which were only about twice the values for the same thickness of asbestos sheet. It is also interesting to compare the 0.001-inch-aluminum-sandwich results with those of specimen M-1-B in figure 5(a). The sandwich is seen to give interface-conductance values comparable with those of the bare interface despite the interposition of an additional layer of material and an additional interface.

The interface-conductance data of figure 6(a) are replotted in figure 6(b) against the dimensionless mean temperature parameter ϕ as a convenience in finding the effect of other combinations of skin thickness, conductivity, and heat flow in the case of sandwich materials within the general scope of the materials tested.

In figure 7 the parameter h_i is plotted against the mean interface temperature. This parameter as applied to a sandwich material can be interpreted as $(t_i/k_i)/(1/h)$ or the ratio of the heat-flow resistance of the interface material to the resistance of the entire interface sandwich consisting of the two interfaces and the sandwich material. As

expected, the metallic sandwich materials provided very little resistance, in the cases tested less than 1/100 of the entire joint resistance. Marked differences may be noted, however, in the effect of the metallic materials on the joint resistance due to influences other than their thickness and conductivity. The 0.010-inch-brass sandwich material is seen to provide approximately nine times the resistance provided by either the 0.002-inch-brass or the 0.001-inch-aluminum sandwich, but nonetheless these resistances are so small relative to the total joint resistance that there is only a 50-percent difference in overall interface resistance between the 0.010-inch brass and the 0.001-inch aluminum
at low mean interface temperatures and virtually no difference at the W
high mean interface temperatures. This may be seen in figure 6 where 1
the reciprocal of the interface conductance may be interpreted as a 3
resistance. 9

The logarithm of the reciprocal of h_i is plotted against the logarithm of ϕ_i in figure 8. There appears to be a relationship which can be interpreted as a linear increase in the logarithm of the relative conductivity of the sandwich material (based on total conductivity across the interface) with the logarithm of the mean interface temperature adjusted for heat flow and for the thickness and conductivity of the sandwich material.

One additional sandwich-material specimen, M-21, was tested. Although its geometric configuration was similar to that of the specimens discussed above, the material of skin and stringer was 17-7 PH stainless steel and the skin thickness was slightly greater, 0.160 inch compared with 0.156 inch. Rivets were AN 427 Monel metal and the interface material was a 0.010-inch-thick Teflon sheet. The interface-conductance data are not plotted in the figures but are as follows: At a mean heat flow of 49,000 Btu/(sq ft)(hr) the average interface-conductance values for two tests were 122, 131, and 126 Btu/(sq ft)(hr)($^{\circ}$F) for mean interface temperatures of 100°, 200°, and 300° F, respectively.

Heat Flow and Interface Pressure

Three specimens (M-15, SU-9, and S-1) were used in an extensive program to determine the effects of heat flow and of pressure at the interface, as determined by torque on the attaching screws, on the interface conductance at various mean interface temperatures.

All specimens were geometrically alike but specimens M-15 and SU-9 were bare at the interface and S-1 was painted with zinc-chromate primer. Specimen SU-9 was one of the carefully machined group fabricated at Syracuse University. Specimen M-15 was tested with both steel and aluminum screws and plain steel nuts; specimen SU-9 was tested with steel screws and plain steel nuts; and specimen S-1, with steel screws and a steel nut with fiber insert.

The effects of heat flow and interface pressure as controlled by screw torque were considered together, since it was only by careful control of the torque that the effects of heat flow could be distinguished.

Specimen M-15.- Considering specimen M-15 first it may be seen in figure 9(a) that for low mean heat-flow rates of 14,000 to 16,000 Btu/(sq ft)(hr) the mean interface-conductance values increased with increasing torque on the steel screws in the range of torque from 10 to 60 inch-pounds. At any given fixed torque the interface conductance decreased with mean interface temperature, a trend which has been apparent from the previously discussed figures. In figure 9(b) for aluminum screws the same general trends are seen but the interface conductance for a torque of 30 inch-pounds is seen to decrease at a greater rate with mean interface temperature than for torques of 20 and 10 inch-pounds. In fact, the final interface conductance at a mean interface temperature of 400° F is lower than the values for the 20- and 10-inch-pound torques. In comparing figures 9(a) and 9(b) it may also be seen that the interface-conductance values are higher for the steel screws than for the aluminum screws at the same torque values and mean interface temperatures, except for the 30-inch-pound torque. In that case the interface conductance for the aluminum-screw test run started higher, $T_m = 100^\circ$ F, and ended lower, $T_m = 400^\circ$ F, than for the steel-screw test run.

In another sequence of tests on specimen M-15 at an intermediate mean heat-flow rate of 58,000 Btu/(sq ft)(hr) the torque was varied between 30 and 100 inch-pounds in increments of 10 inch-pounds. In each test the torque was increased to the test value after loosening the screws from their previous torque values. Steel screws were used in this sequence. The complete data are not presented, but the following maximum and minimum values were found:

Interface conductance, Btu/(sq ft)(hr), at T_m, °F, of -			
	100	200	300
Maximum	1,044	935	892
Minimum	1,008	895	840

The values are seen to lie within a very narrow range with a maximum difference of 6 percent at any mean interface temperature. No discernible trend of interface conductance with respect to torque, as seen in figures 9(a) and 9(b), was apparent upon examination of the data.

In the tests for which the data were presented in figures 9(a) and 9(b) the mean heat-flow rate was kept approximately constant and the torque on the screws was varied. In figures 9(c) and 9(d) results are presented for a series of tests at each of two constant values of torque on steel screws in which the mean heat-flow rate was varied from test to test. In both cases interface-conductance values were found to increase with heat-flow rate at any given mean interface temperature and to decrease with increasing mean interface temperature for a fixed heat-flow rate.

An attempt was made to compare the effect on interface conductance of tightening only the screws on either side of the test section with tightening all of the screws. Comparative tests were conducted at 20 inch-pounds and 80 inch-pounds. Very little difference was found in the interface conductance; in both cases tightening all of the screws led to less than a 5-percent increase in interface-conductance values over those found for tightening only the screws adjacent to the test section. The data for these tests have not been presented.

In figure 9(e) the mean interface conductance is plotted against the nondimensional parameter ϕ for the heat-flow range of 12,000 to 134,000 Btu/(sq ft)(hr) for a torque of 60 inch-pounds on the steel screws. The interface-conductance values are those presented in figure 9(d).

Specimen SU-9.- Considering specimen SU-9 which was geometrically identical in every way with the previously discussed specimen M-15, it may be seen in figure 10(a) that at all three heat flows the general tendency is for the interface conductance to decrease with increase in the screw torque, with the exception of the 20-inch-pound torque above a mean interface temperature of 400° F. This general tendency is opposite to that found for specimen M-15 where the interface conductance increased with an increase in torque (see figs. 9(a) and 9(b)). This difference in behavior of the two specimens is considered further in connection with the results for specimen S-1.

The effect of heat-flow rate on the interface conductance at various mean interface temperatures is shown in figure 10(b) for a torque on the screws of 20 inch-pounds and in figure 10(c) for a torque of 60 inch-pounds. The data presented are comparable with those presented in figures 9(c) and 9(d) for specimen M-15. It may be noted that, as in these previous figures, the interface conductance increases as the heat flow increases and decreases with mean interface temperature. The average interface conductance for five tests at a heat-flow rate of 54,000 Btu/(sq ft)(hr) and for 25 tests at 8,000 to 9,000 Btu/(sq ft)(hr) are plotted in figure 10(b) for comparison with the results for single tests at the various heat-flow rates. The curve for the heat-flow rate of 54,000 Btu/(sq ft)(hr) falls as expected between 50,000 and 126,000 Btu/(sq ft)(hr), but the curve for 8,000 to 9,000 Btu/(sq ft)(hr) is higher than the curve for 11,000 Btu/(sq ft)(hr). It should be noted, however, that the average curve is for 25 tests compared with a single test in the case of the curve for 11,000 Btu/(sq ft)(hr).

Specimen S-1.- Specimen S-1 was the pilot specimen for the torque tests and was not tested as extensively as specimens M-15 and SU-9. In the tests of this specimen the mean heat-flow rate was kept nearly constant at values of 31,000 to 34,000 Btu/(sq ft)(hr) and the torque was increased on the screws from zero to 60 inch-pounds in 15-inch-pound increments, and then decreased in the same manner. At each increment of torque on the screws a complete test was carried out to a mean interface temperature of approximately 300° F.

The interface-conductance values for tests with various increments of torque on the screws are presented in figure 11 as a function of mean interface temperature. The values of interface conductance for the zero-torque condition are average values for two tests before torque was applied and two tests after torque was applied; the values for the 60-inch-pound-torque increment are the average of the three tests which were run at that increment. All other values are for a single test at increasing torque increment. The values for decreasing torque increment were not plotted since they differed very little from the values at increasing increments.

A comparison of the behavior of the interface conductance of specimen S-1 with that of specimen M-15 (figs. 9(a) and 9(b)) is of some interest. In both specimens the effect of increased torque on the screws is to increase the interface conductance at a given mean interface temperature. Unlike specimen M-15, however, the interface conductance for specimen S-1 increases slightly with mean interface temperature. This increase in interface conductance with mean interface temperature for specimen S-1 was not a consistent characteristic behavior for the specimens tested in the entire program. Although occasionally an individual test showed an increase, most specimens showed decreasing interface conductance with mean interface temperature, or very little change at all, and it is interesting to note that where there was an increase, as, for example, in specimen S-1, the increase was not great. The specimens whose interfaces were painted with zinc-chromate primer showed generally the least tendency for the interface conductance to vary with mean interface temperature (see, for example, figs. 5(b) and 5(c)).

The variation of interface conductance with torque on the screws for all three specimens (M-15, SU-9, and S-1) is plotted in figure 12 at the same mean interface temperature of 200° F. Although there is some difference in the heat-flow values for which the data are presented, this difference is not believed to be significant.

For two of the three specimens the interface conductance increases with torque on the screws. This increase could, of course, logically be attributed to an increased pressure at the interface which has been shown in previous experiments (ref. 2) to cause an increase in interface conductance. But this leaves the opposite behavior of specimen SU-9 to be explained. A possible explanation is that strains created by tightening of the screws move or warp the contact surfaces with respect to each other, and that in this case the movement or warping is such that it decreases the number or area of spots in contact or increases the gap between the surfaces and thus decreases the interface conductance. It is of course understood that this assumed movement or warping may also have influenced specimens M-15 and S-1 in either the same or the opposite way; some of the increase for those specimens may be attributed to movement or warping as well as to direct pressure effects (which in themselves may be considered warping) or may have reduced the expected increase due to increased pressure. It is also possible that thermal warping, as distinguished from the foregoing mechanical warping, influences the interface conductance since the temperature drop across the interface is different from specimen to specimen even where the heat flow is substantially the same.

In order to confirm, if possible, the aforementioned conjectures regarding warping, specimen SU-9 was subjected to three types of warping tests, after replacement of all thermocouples and a recheck of several previous test conditions. The results are shown in figure 13 where interface conductance is plotted against mean interface temperature at screw torques of 20 and 80 inch-pounds for three different conditions.

In the first condition only the screws adjacent to the test cross section were torqued; all other screws were finger tight. As before (see fig. 10(a)) the higher torque gave the lowest interface-conductance values throughout the mean-interface-temperature range, but with a lesser effect of torque difference on interface conductance. Contrary to figure 10(a) but in accord with figure 11 the interface conductance is seen to increase rather than decrease with mean interface temperature.

In the second condition a brass shim strip was inserted under the leg of the stringer for its entire length in order to rotate the angle with respect to the sheet prior to applying torque to all of the screws and thus to induce initial warping. For this condition the initial values of interface conductance for both 20 and 80 inch-pounds at

$T_m = 100^\circ$ F are appreciably higher than for the first condition. At 20 inch-pounds the interface conductance increases and at 80 inch-pounds it decreases from these initial values.

In the third condition two fine wires were laid across the interface on either side of the test section prior to tightening all of the screws. The resulting effect on the interface conductance is similar to the effect of the shim except that the interface-conductance values are somewhat lower.

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It is believed that in the above three tests some warping was induced which accounted for the varied behavior of the interface conductance, but it must be realized that other factors such as change in gap and introduction of foreign material as a heat path were introduced at the same time.

Material Combinations

Since steel and titanium-alloy skins with a light alloy web have been suggested as promising combinations for stress alleviation in heated structures it was considered desirable to determine the interface conductance for some of these combinations. The test program, therefore, included such specimens (M-22 and B-2), as well as combinations of like materials other than aluminum alloys (M-20, B-1, and B-3). Since these specimens were all fabricated with Monel rivets, a group of three aluminum-alloy specimens (M-11-B, N-13-A, and R-10-A) with similar rivets was used as a control. Specimens B-1, B-3, and M-20 were made with a bent-up angle stringer in accordance with figure 3(b); the others were in accordance with figure 3(a). Also specimen B-3 had a slightly thicker stringer of 0.160 inch as compared with 0.156 inch for the remaining specimens.

The interface-conductance values for these combinations are presented in figure 14. It is noted that these interface-conductance values are among the lowest found for any skin-stringer combinations reported here; for example the Inconel X (specimen B-1) and the 6Al-4V titanium alloy (specimen B-3) interface-conductance values of approximately 150 to 200 Btu/(sq ft)(hr)($^\circ$F) are comparable with those for aluminum-alloy specimens with asbestos sandwiches at the interface (see fig. 6). It is also interesting to compare these values with the stainless-steel joints of reference 1 (fig. 8(d)) where the roughest surfaces, 100 to 120 microinches root mean square, gave interface-conductance values in the neighborhood of 300 Btu/(sq ft)(hr)($^\circ$F), but values of up to five times as great were found with smooth surfaces of 20 to 60 microinches root mean square.

The interface conductance for the Inconel X and 17-7 PH stainless-steel specimens with aluminum-alloy stringers (M-22 and B-2) was higher throughout the mean-interface-temperature range than for counterpart specimens with the stringer made of the same material as the skin (M-20 and B-1).

Two of the three control specimens of aluminum-alloy skin with stringers of the same material (M-11-B and N-13-A) were among the few specimens in the entire program whose interface conductance increased with mean interface temperature, but the increase was not very great. The third specimen of this type (R-10-A) showed no change in interface conductance with mean interface temperature.

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Type of Connection

In order to determine the effect of the type of connection used between skin and stringer on interface conductance, a series of 43 specimens were tested. These specimens were fabricated in accordance with figure 3(a) by three different manufacturers who were requested to supply a representative connection, both as to choice of type and as to manufacturing technique. The specimens were all geometrically identical.

The interface-conductance values resulting from the test are presented in table II which also repeats the type of connection. For every connection type at least two tests were conducted; the interface-conductance values presented are the average values for these tests at mean interface temperatures of 100°, 200°, 300°, and 400° F, except where the highest temperature of 400° F was not attained. The mean heat flows into the specimen for each test run were calculated; the averages of these heat flows for each connection type are presented in table II.

The interface-conductance values presented in table II must be interpreted in the light of what has been said previously about manufacturing variability. It is not intended that the designer choose interface-conductance values for a given connection type as fixed values, but only as representative values with the possibility of considerable variability. Perhaps a more meaningful way of looking at these data is to consider the various connections in a rough order of merit from those giving the highest to those giving the lowest interface-conductance values. The use of the term "order of merit" in the sense of highest to lowest values is only arbitrary since in a given case either high or low values may be desirable. In order to present a ranking from high to low values of interface conductance the average values for interface conductance at $T_m = 300^\circ$ F have been selected from table II as most nearly representative and are presented in table III. It is apparent that had some other value of mean interface temperature been chosen there would be some changes in the order of listing, but it is felt that the range is more important than the specific rank, especially in view of the probable manufacturing variability which has not been taken into account.

Two of the specimens (M-14 and N-16) included in table II had a skin thickness of 0.313 inch as compared with 0.156 inch for the remainder of the specimens, and they thus have been omitted from the ranking of table III.

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An examination of the entire range of values presented in table III reveals several items of interest. The highest average value of interface conductance shown, 1,076 Btu/(sq ft)(hr)(^{o}F) for the NAS517 screw, is more than ten times greater than the value of 103 Btu/(sq ft)(hr)(^{o}F) for the P-565-204-100 exploding rivet. It can also be seen that in general the alloy-steel screws, high-shear pins, and lockbolts give the highest values of interface conductance and the blind- and exploding-type rivets, the lowest. One exception to this generalization is seen to be specimen M-9-A; in this specimen the high-shear pin shows a low interface-conductance value of 199 Btu/(sq ft)(hr)(^{o}F).

In examining the range of interface-conductance values individual high and low values should be considered in addition to the average values presented in the preceding tables. Therefore table IV has been prepared to present the complete test sequences for specimens M-13 and N-11-B which were the two specimens giving highest and lowest interface-conductance values. Here it may be seen that the highest interface-conductance value achieved was 2,154 Btu/(sq ft)(hr)(^{o}F) and the lowest, 84 Btu/(sq ft)(hr)(^{o}F), both at a mean interface temperature of 100^{o} F. Thus the ratio between highest and lowest becomes over 25 to 1 compared with the aforementioned 10 to 1 for the averages at a mean interface temperature of 300^{o} F.

Heating History

One of the most difficult problems in the analysis of interface-conductance data has been the variation in test values in any sequence of tests on the same specimen. In order to test the hypothesis that heating history could account for some of the variation, a group of specimens was prepared in which each specimen could be followed carefully as to its history, and the interface pressure as determined by torque on the screw fastenings could be held constant for each test.

These specimens were made as nearly identical as possible by careful fabrication which included machining of the stringer-contact face and checking its flatness and surface roughness. The various phases of the fabrication process were carried out as nearly as possible under the same conditions for each specimen. New drills and milling cutters were used on each specimen, the depth of cuts was kept similar, and cleaning and final assembly were done in the laboratory rather than in the machine shop.

By making a group of identical specimens it also became possible to compare the variability in interface conductance with the variability of specimens from a number of manufacturing sources as previously presented in this report.

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The nine available specimens were divided into two subgroups of four and five specimens, respectively. The first subgroup of four was used as a control to test the uniformity of interface-conductance values of geometrically identical specimens with identical histories up to and during testing. Each of these specimens was tested four times at intervals of 24 hours under the same heat flow of 8,000 Btu/(sq ft)(hr) and with the screws torqued to 20 inch-pounds. The resultant interface-conductance values are presented in figure 15 in the form of averages for the four test runs, with the highest and lowest single value for any test also given, at each of four mean interface temperatures.

It is seen that the variability of interface conductance from specimen to specimen is substantial despite all the precautions taken to make the specimens identical and to test them under identical conditions. The amount of variability, however, appears to be considerably less than that for specimens fabricated with no attempt to hold other than to geometrical identity and normal test conditions. For example, at a mean temperature of 100° F the difference shown in figure 15 between specimens SU-10 and SU-11 is less than half the difference between specimens M-1-B and R-1-C indicated in figure 5(a).

The general trend of interface conductance appears to be similar to that for most of the specimens in the test program, that is, a decrease with increasing mean interface temperature. However, the decrease of the interface conductance with increasing mean interface temperature is not linear as was the case for the specimens in figure 5(a).

From the results of the tests on this subgroup of four specimens it was concluded that subsequent tests to determine the effects of heating history would have to be limited to the effect of the history on each specimen as an individual, and that no comparison between specimens could be made. This must be borne in mind in examining figure 16 where the interface-conductance values presented are average values for 25 consecutive tests for each specimen (except for SU-12) at intervals between tests of 15 minutes, $2\frac{1}{2}$ hours, 24 hours, 10 days, and 104 days for the subgroup of five specimens, SU-9, SU-7, SU-2, SU-4, and SU-12, respectively. Specimen SU-12 was tested only three times because of the length of time required between tests.

The variability of interface conductance for this subgroup of five specimens is seen to be greater than that for the previously discussed subgroup of four. It would appear at first glance that the interval between tests increased the variability of interface conductance between identical specimens. This is negated, however, by the fact that the variability in figure 16 is substantially increased by specimen SU-2 which was tested at the same 24-hour intervals as were the specimens shown in figure 15. Thus, were specimen SU-2 included with the control subgroup of figure 15 (despite the increased number of tests), the control subgroup would show greater variability than the group of figure 16.

In figure 16 the range of interface conductance at a mean interface temperature of 100° F is seen to be nearly as great as for the group of specimens of figure 5(a). If the complete group of nine specimens of figures 15 and 16 is considered, the spread at 100° F is slightly greater than that for the specimens of figure 5(a). It would thus appear that the manufacturing variables which affect the interface conductance are not readily amenable to control.

The heating-history effect for a single specimen is perhaps best illustrated by presentation of the detailed data for specimen SU-9 which is representative of that available for specimens in the group presented in figure 16. The interface-conductance values for the 25 consecutive tests on specimen SU-9 are presented in table V: The interval between each test was 15 minutes and each test took approximately 90 seconds to perform from the time the heating lamps were turned on.

The data for the subgroup of five, of which table V gives typical values, were examined by statistical methods for trends and deviations from randomness. For each of four mean interface temperatures, calculations were made of the mean and median values of interface conductance as well as of the standard deviation. The results of these calculations are presented in table VI. Trend lines for the data were calculated by the method of least squares and are presented in figure 17 for the typical specimen SU-9.

Several types of control charts were constructed to test the data for trends in accordance with the methods of reference 7. In the first of these the data were divided into subsets of four, the subsets summed, the mean of all subsets and the range of each subset determined, and the mean of the ranges used to calculate the standard deviation of the subset sums. The subset sums were then plotted in the order of their determination for comparison with this standard deviation. The plotted data (not presented in this report) showed for all cases where the foregoing calculations were made that subset sums lay within ±3 standard deviations. In some cases, specimen SU-7 for example, the subset sums lay within ±2 standard deviations. Since the series of data are judged to be sufficiently long to give a good estimate of the standard deviation it appears that the interface-conductance values vary in a random fashion without significant jumps or trends.

In the second type of control chart the range of each subset of four was plotted against the ordinal number of the subset and compared with control limits computed from the distribution function for the range. The control limit used was from zero to 2.28 times the mean range of the separate subsets. This type of chart can be used to detect trends or jumps in precision. None were found.

Tests for the number and length of runs in the interface-conductance data of table V were checked against the critical values of reference 7. Again no trends in the data could be found.

It was concluded from the foregoing statistical tests that the hypothesis could be adopted that the interface conductance does not show any variation with length of time between tests.

CONCLUSIONS

The following conclusions were derived from examination of the experimental results of transient heating tests on skin-stringer panels:

1. The interface conductance may vary considerably for seemingly identical specimens manufactured at the same plant; a similar range of variability is found in identical specimens fabricated under extremely careful laboratory conditions.

2. Skin thickness has some effect on interface conductance, but this may be obscured by manufacturing variability.

3. No significant effect of cleanliness of the joint on interface conductance could be found.

4. The rate of heat flow into the specimen has a pronounced effect on the interface conductance. In most cases the interface conductance increases with increasing rate of heat flow, but this trend may be obscured unless interface pressure between skin and stringer is carefully controlled by means such as screw torque.

5. The interface conductance usually increases with an increase of torque on the screws attaching the skin to the stringer, but there can be exceptions.

6. In specimens with a sandwich material at the interface the good conductors give high interface-conductance values, but factors other than the thickness and conductivity of the sandwich material appear to be significant.

7. In specimens of various material combinations the lowest interface-conductance values were found for the Inconel X and 6Al-4V titanium alloy. The interface conductance for these specimens was found to be comparable with that of a specimen of aluminum alloy with an asbestos sandwich material at the interface.

8. The type of connection used for a skin-stringer combination may have an appreciable effect on the interface conductance. Interface-conductance values varying by as much as 10 to 1 may be expected at the same mean interface temperature. The ratio between the highest and lowest value may be as great as 25 to 1.

9. In comparing the effect of types of connections on the interface conductance the alloy steel screws, high-shear pins, and lockbolts give the highest values of interface conductance and the blind- and exploding-type rivets the lowest, but there may be an occasional exception.

10. The interface conductance does not vary with the length of time between tests.

Syracuse University,
Syracuse, N.Y., June 1, 1959.

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TABLE I

DESCRIPTION OF SPECIMENS

(a) Configuration, material, and interface condition

[All specimens had a flange thickness of 1.25 inches, flange length in cross section of 1.25 inches, web length in cross section of 1.25 inches, 0.625-inch distance to rivet center line, and a rivet pitch of 1.00 inch]

Specimen	Skin thickness, t_s, in.	Material (a)		Interface condition or sandwich material
		Skin	Angle	
M-1-A	0.156	2024-T3	2024-T	Bare, clean
M-1-B	.156	--do---	--do---	Bare, clean
M-2-A	.156	--do---	--do---	Bare, dirty
M-2-B	.156	--do---	--do---	Bare, dirty
M-3-A	.313	--do---	--do---	Bare, clean
M-3-B	.313	--do---	--do---	Do.
M-4	.156	--do---	--do---	Do.
M-5	.156	--do---	--do---	Do.
M-6	.156	--do---	--do---	Do.
M-7-A	.156	--do---	--do---	Do.
M-7-B	.156	--do---	--do---	Do.
M-8-A	.156	--do---	--do---	Do.
M-8-B	.156	--do---	--do---	Do.
M-9-A	.156	--do---	--do---	Do.
M-9-B	.156	--do---	--do---	Do.
M-10-A	.156	--do---	--do---	Do.
M-10-B	.156	--do---	--do---	Do.
M-11-A	.156	--do---	--do---	Do.
M-11-B	.156	--do---	--do---	Do.
M-12-A	.156	--do---	--do---	Do.
M-12-B	.156	--do---	--do---	Do.
M-13	.156	--do---	--do---	Do.
M-14	.313	--do---	--do---	Do.
M-15	.156	--do---	--do---	Do.
M-16	.156	--do---	--do---	Do.
M-17-A	.156	--do---	--do---	0.010-in.-thick aluminum sheet
M-17-B	.156	--do---	--do---	0.001-in.-thick aluminum sheet
M-18-A	.156	--do---	--do---	0.010-in.-thick brass shimstock
M-18-B	.156	--do---	--do---	0.002-in.-thick brass shimstock
M-19-A	.156	--do---	--do---	0.010-in.-thick sheet asbestos
M-19-B	.156	--do---	--do---	0.031-in.-thick sheet asbestos
M-20	.160	17-7 PH	17-7 PH	Bare
M-21	.160	--do---	--do---	0.010-in.-thick Teflon sheet
M-22	.160	--do---	2024-T	Bare
N-1-A	.156	2024-T	2024-T	Zinc-chromate primer, clean
N-1-B	.156	--do---	--do---	Do.
N-2-A	.156	--do---	--do---	Zinc-chromate primer, dirty
N-2-B	.156	--do---	--do---	Do.
N-3-A	.313	--do---	--do---	Bare
N-3-B	.313	--do---	--do---	Do.
N-6	.156	--do---	--do---	Zinc-chromate primer
N-7	.156	--do---	--do---	Do.
N-8	.156	--do---	--do---	Do.
N-9-A	.156	--do---	--do---	Do.
N-10-A	0.156	2024-T	2024-T	Zinc-chromate primer
N-10-B	.156	---do----	---do----	Do.
N-11-A	.156	---do----	---do----	Do.
N-11-B	.156	---do----	---do----	Do.
N-12-A	.156	---do----	---do----	Do.
N-12-B	.156	---do----	---do----	Do.
N-13-A	.156	---do----	---do----	Do.
N-13-B	.156	---do----	---do----	Do.
N-14-A	.156	---do----	---do----	Do.
N-14-B	.156	---do----	---do----	Do.
N-15	.156	---do----	---do----	Do.
N-16	.313	---do----	---do----	Bare
R-1-A	.156	2024-T	2024-T	Bare
R-1-B	.156	---do----	---do----	Do.
R-1-C	.156	---do----	---do----	Do.
R-1-D	.156	---do----	---do----	Do.
R-2-A	.313	---do----	---do----	Do.
R-2-B	.313	---do----	---do----	Do.
R-2-C	.313	---do----	---do----	Do.
R-2-D	.313	---do----	---do----	Do.
R-3	.156	---do----	---do----	Do.
R-4	.156	---do----	---do----	Do.
R-5	.156	---do----	---do----	Do.
R-7-A	.156	---do----	---do----	Do.
R-7-B	.156	---do----	---do----	Do.
R-8	.156	---do----	---do----	Do.
R-9	.156	---do----	---do----	Do.
R-10-A	.156	---do----	---do----	Do.
R-10-B	.156	---do----	---do----	Do.
B-1	.156	Inconel X	Inconel X	Bare
B-2	.156	---do----	2024-T	Do.
B-3	.156	6Al 4V	6Al 4V	Do.
S-1	.156	2024-T	2024-T	Zinc-chromate primer
SU-1	.156	2024-T3	2024-T	Bare, machined angle
SU-2	.156	Alclad	---do----	Do.
SU-4	.156	---do----	---do----	Do.
SU-7	.156	---do----	---do----	Do.
SU-8	.156	---do----	---do----	Do.
SU-9	.156	---do----	---do----	Do.
SU-10	.156	---do----	---do----	Do.
SU-11	.156	---do----	---do----	Do.
SU-12	.156	---do----	---do----	Do.

[a]Designations are for aluminum alloy unless otherwise specified.

TABLE I.- Continued

DESCRIPTION OF SPECIMENS

(b) Skin-stringer connections

Specimen	Connection designation	Type	Head	Diameter, in.	Material (a)
M-1-A	AN426-DD	Solid rivet	100° countersunk	3/16	2024-T
M-1-B	--------do--------	------do------	-------do-------	3/16	Do.
M-2-A	--------do--------	------do------	-------do-------	3/16	Do.
M-2-B	--------do--------	------do------	-------do-------	3/16	Do.
M-3-A	--------do--------	------do------	-------do-------	3/16	Do.
M-3-B	--------do--------	------do------	-------do-------	3/16	Do.
M-4	AN470-A	------do------	Universal	3/16	1100
M-5	AN470-DD	------do------	-------do-------	3/16	2024-T
M-6	AN470-AD	------do------	-------do-------	3/16	2117-T
M-7-A	TLP/D/BH	Tubular rivet	Protruding	3/16	Monel
M-7-B	TLP/KR/BH	------do------	100° countersunk	3/16	Do.
M-8-A	MS 20600	Cherry rivet	Universal	3/16	2117-T rivet, 2017-T stem
M-8-B	MS 20601	------do------	100° countersunk	3/16	Do.
M-9-A	HS 68 rivet	Hi-shear pin		3/16	Type 431 stainless-steel rivet
	NAS179 collar	------do------	Flat	3/16	2117-T collar
M-9-B	HS 67 rivet	------do------		3/16	Do.
	NAS179 collar	------do------	100° countersunk	3/16	Do.
M-10-A	HS 48 rivet	------do------		3/16	Alloy steel rivet
	NAS179 collar	------do------	Flat	3/16	2117-T collar
M-10-B	HS 47 rivet	------do------		3/16	Do.
	NAS179 collar	------do------	100° countersunk	3/16	Do.
M-11-A	AN435-M	Solid rivet	Round	3/16	Monel
M-11-B	AN427-M	------do------	100° countersunk	3/16	Do.
M-12-A	ALPPH-T bolt			3/16	Alloy steel bolt
	LC-F collar	Lockbolt	Pan	3/16	6061-T6 collar
M-12-B	ACT 509H-T bolt	------do------		3/16	Alloy steel bolt
	LC-C collar	------do------	100° countersunk	3/16	2024-T4 collar
M-13	NAS517 screw			3/16	Alloy steel screw
	AN363 nut	Screw and nut	100° countersunk	3/16	Steel nut
M-14	--------do--------	------do------	-------do-------	3/16	Do.
M-15	(1) AN509-DD screw	------do------	-------do-------	3/16	2024-T4 screw
	(2) Steel screw	------do------	-------do-------	3/16	Steel screw
	AN363 nut, self-locking	------do------	-------do-------	3/16	Steel nut
M-16	------------------	Spotweld	----------------	----	------------------------------
M-17-A	AN426-DD	Solid rivet	100° countersunk	3/16	2024-T
M-17-B	--------do--------	------do------	-------do-------	3/16	Do.
M-18-A	--------do--------	------do------	-------do-------	3/16	Do.
M-18-B	--------do--------	------do------	-------do-------	3/16	Do.
M-19-A	--------do--------	------do------	-------do-------	3/16	Do.
M-19-B	--------do--------	------do------	-------do-------	3/16	Do.
M-20	AN427-M	------do------	-------do-------	3/16	Monel
M-21	--------do--------	------do------	-------do-------	3/16	Do.
M-22	--------do--------	------do------	-------do-------	3/16	Do.
N-1-A	AN426-DD	Solid rivet	100° countersunk	3/16	2024-T
N-1-B	--------do--------	------do------	-------do-------	3/16	Do.
N-2-A	--------do--------	------do------	-------do-------	3/16	Do.
N-2-B	--------do--------	------do------	-------do-------	3/16	Do.
N-3-A	--------do--------	------do------	-------do-------	3/16	Do.
N-3-B	--------do--------	------do------	-------do-------	3/16	Do.
N-6	AN426-A	------do------	-------do-------	3/16	1100
N-7	AN470-DD	------do------	Universal	3/16	2024-T
N-8	AN470-AD	------do------	-------do-------	3/16	2117-T
N-9-A	AN450-C12	Tubular rivet	Oval	3/16	Mild steel
N-10-A	CR163	Cherry rivet	Universal	3/16	2117-T rivet, 2017-T stem

[a]Designations are for aluminum alloy unless otherwise specified.

TABLE I.- Concluded

DESCRIPTION OF SPECIMENS

(b) Skin-stringer connections - Concluded

Specimen	Connection designation	Type	Head	Diameter, in.	Material (a)
N-10-B	CR 563	Cherry rivet	Universal	3/16	Monel rivet and stem
N-11-A	P-565-204-A	Exploding rivet	Brazier	3/16	5056
N-11-B	P-565-204-100	-------do------	100° countersunk	3/16	Do.
N-12-A	NAS177 rivet		-------do-------	3/16	Alloy steel rivet
	HS 60 collar	Hi-shear pin	-------do-------	3/16	Type 321 stainless steel collar
N-12-B	NAS178 rivet	-------do------		3/16	Alloy steel rivet
	HS 15 collar	-------do------	Flat	3/16	2024-T4 collar
N-13-A	AN427-M	Solid rivet	100° countersunk	3/16	Monel
N-13-B	NAS508-M	-------do------	Oval	3/16	Do.
N-14-A	ALPPH-E bolt			3/16	7075-T6 bolt
	LC-F collar	Lockbolt	Pan	3/16	6061-T6 collar
N-14-B	ALPPH-T bolt	-------do------	-------do-------	3/16	Alloy steel bolt
	LC-C collar			3/16	2024-T4 collar
N-15	AN509-C screw			3/16	Corrosion resistant steel screw
	AN365 nut	Screw and nut	100° countersunk	3/16	Steel nut
N-16	-------do-------	-------do------	-------do-------	3/16	Do.
R-1-A	AN426-DD	Solid rivet	100° countersunk	3/16	2024-T
R-1-B	-------do-------	-------do------	-------do-------	3/16	Do.
R-1-C	-------do-------	-------do------	-------do-------	3/16	Do.
R-1-D	-------do-------	-------do------	-------do-------	3/16	Do.
R-2-A	-------do-------	-------do------	-------do-------	3/16	Do.
R-2-B	-------do-------	-------do------	-------do-------	3/16	Do.
R-2-C	-------do-------	-------do------	-------do-------	3/16	Do.
R-2-D	-------do-------	-------do------	-------do-------	3/16	Do.
R-3	AN426-A	-------do------	-------do-------	3/16	1100
R-4	AN456-DD	-------do------	Universal	3/16	2024-T
R-5	AN456-AD	-------do------	-------do-------	3/16	2117-T
R-7-A	CR 363	Cherry rivet	-------do-------	3/16	Steel rivet and stem
R-7-B	CR 179	-------do------	-------do-------	3/16	2117-T rivet, 2017-T stem
R-8	MS 20602	Exploding rivet	Brazier	5/32	2117-T
R-9	HS 2R7 rivet			3/16	Alloy steel rivet
	HS 15 collar	Hi-shear pin	100° countersunk	3/16	2024-T4 collar
R-10-A	AN427-M	Solid rivet	-------do-------	3/16	Monel
R-10-B	AN435-M	-------do------	Round	3/16	Do.
B-1	AN427-M	Solid rivet	100° countersunk	3/16	Monel
B-2	-------do-------	-------do------	-------do-------	3/16	Do.
B-3	-------do-------	-------do------	-------do-------	3/16	Do.
S-1	AN509 screw	Screw and nut	100° countersunk	3/16	Steel screw
	AN365-A nut				Steel nut, fiber insert
SU-1	Commercial 10-32 steel screw	Screw and nut	80° countersunk	3/16	18-8 stainless steel screw, hexagonal nut and washer
SU-2	-------do-------	-------do------	-------do-------	3/16	Do.
SU-4	-------do-------	-------do------	-------do-------	3/16	Do.
SU-7	-------do-------	-------do------	-------do-------	3/16	Do.
SU-8	-------do-------	-------do------	-------do-------	3/16	Do.
SU-9	-------do-------	-------do------	-------do-------	3/16	Do.
SU-10	-------do-------	-------do------	-------do-------	3/16	Do.
SU-11	-------do-------	-------do------	-------do-------	3/16	Do.
SU-12	-------do-------	-------do------	-------do-------	3/16	Do.

[a]Designations are for aluminum alloy unless otherwise specified.

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TABLE II

INTERFACE-CONDUCTANCE DATA FOR 43 GEOMETRICALLY IDENTICAL SPECIMENS WITH VARIOUS CONNECTIONS

[Unless otherwise specified, all specimens had a skin thickness of 0.156 inch, flange length in cross section of 1.25 inches, web length in cross section of 1.25 inches, 0.625-inch distance to rivet center line, and rivet pitch of 1.00 inch]

Specimen	Connection designation	Number of tests	Average of mean heat flows, Btu/(sq ft)(hr)	Average interface conductance, Btu/(sq ft)(hr)(°F), at T_m, °F, of -			
				100	200	300	400
N-6	AN426-A	2	34,500	778	635	524	465
N-7	AN470-DD	4	35,250	691	650	547	---
N-8	AN470-AD	2	35,000	917	783	691	658
N-9-A	AN450-C	2	33,000	420	426	419	415
N-10-A	CR 163	2	33,500	556	583	528	486
N-10-B	CR 563	2	35,000	681	686	587	---
N-11-A	P-565-204-A	2	34,500	168	162	161	---
N-11-B	P-565-204-100	2	34,000	93	103	103	---
N-12-A	NAS177 rivet HS 60 collar	2	33,000	1,132	963	895	918
N-12-B	NAS178 rivet HS 15 collar	2	34,000	1,051	1,028	950	885
N-13-A	AN427-M	4	58,000	368	411	424	---
N-13-B	NAS508-M	2	36,000	563	583	566	535
N-14-A	ALPPH-E bolt LC-F collar	2	37,500	614	579	562	---
N-14-B	ALPPH-T bolt LC-C collar	2	32,500	621	528	460	403
N-15	AN509-C screw AN365 nut	2	34,500	644	588	545	522
[a]N-16	AN509-C screw AN365 nut	2	41,000	703	603	478	416
M-4	AN407-A	2	12,000	377	339	303	243
M-5	AN470-DD	4	12,000	836	785	711	742
M-6	AN470-AD	2	10,000	1,042	777	629	649
M-7-A	TLP/D/BH	2	12,000	468	435	412	435
M-7-B	TLP/KR/BH	3	24,600	468	441	394	364
M-8-A	MS 20600	2	13,000	236	239	231	240
M-8-B	MS 20601	2	12,500	316	275	235	214
M-9-A	HS 68 rivet NAS179 collar	2	12,000	207	198	199	---
M-9-B	HS 67 rivet NAS179 collar	2	11,500	802	719	648	533
M-10-A	HS 48 rivet NAS179 collar	2	11,500	537	551	467	485
M-10-B	HS 47 rivet NAS179 collar	4	12,000	463	445	384	361
M-11-A	AN435-M	2	15,000	596	486	367	---
M-11-B	AN427-M	4	58,500	721	776	788	---
M-12-A	ALPPH bolt LC-F collar	4	11,750	1,298	1,108	873	769
M-12-B	ACT 509H-T bolt LC-C collar	2	14,000	1,180	1,110	917	758
M-13	NAS 517 screw AN363 nut	4	14,500	1,749	1,364	1,076	949
[a]M-14	NAS 517 screw AN363 nut	2	16,000	907	640	448	---
M-15	AN509-DD screw AN363 nut	[b]2	13,500	1,152	918	744	606
M-16	Spotweld	2	16,000	908	806	673	633
R-3	AN426-A	2	15,000	411	482	481	494
R-4	AN456-DD	2	16,000	806	727	594	542
R-5	AN456-DD	3	27,000	447	429	386	---
R-7-A	CR 363	2	17,000	190	199	205	---
R-7-B	CR 179	2	15,000	175	183	175	175
R-8	MS 20602	2	18,000	112	131	134	140
R-9	HS 27R 7 rivet HS 15 collar	2	17,500	432	402	361	348
R-10-A	AN427-M	4	54,250	314	327	322	---
R-10-B	AN435-M	2	15,000	315	345	357	374

[a]Skin thickness, 0.313 in.

[b]Other extensive tests on this specimen are reported elsewhere in this report.

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TABLE III

RANGE OF INTERFACE CONDUCTANCE FOR VARIOUS CONNECTION TYPES AT A MEAN INTERFACE TEMPERATURE OF 300° F

Specimen	Connection designation	Average interface conductance at T_m = 300° F, Btu/(sq ft)(hr)(°F)	Specimen	Connection designation	Average interface conductance at T_m = 300° F, Btu/(sq ft)(hr)(°F)
M-13	NAS517	1,076	M-10-A	HS 48	467
N-12-B	NAS178	950	N-14-B	ALPPH-T	460
M-12-B	ACT 509H-T	917	N-13-A	AN427-M	424
N-12-A	NAS177	895	N-9-A	AN450-C	419
M-12-A	ALPPH	873	M-7-A	TLP/D/BH	412
M-11-B	AN427-M	788	M-7-B	TLP/KR/BH	394
M-15	AN509-DD	744	R-5	AN456-AD	386
M-5	AN470-DD	711	M-10-B	HS47	384
N-8	AN470-AD	691	M-11-A	AN435-M	367
M-16	Spotweld	673	R-9	HS 2R7	361
M-9-B	HS 67	648	R-10-B	AN435-M	357
M-6	AN470-AD	629	R-10-A	AN427-M	322
R-4	AN456-DD	594	M-4	AN470-A	303
N-10-B	CR 563	587	M-8-B	MS 20601 (CR 162)	235
N-13-B	NAS508-M	566	M-8-A	MS 20600 (CR 163)	231
N-14-A	ALPPH-E	562	R-7-A	CR 363	205
N-7	AN470-DD	547	M-9-A	HS 68	199
N-15	AN509-C	545	R-7-B	CR 179	175
N-10-A	CR 163	528	N-11-A	P-565-204-A	161
N-6	AN426-A	523	R-8	MS 20602	134
R-3	AN426-A	481	N-11-B	P-565-204-100	103

TABLE IV

COMPLETE INTERFACE-CONDUCTANCE DATA FOR CONNECTION SPECIMENS SHOWING HIGHEST AND LOWEST INTERFACE-CONDUCTANCE VALUES

Specimen	Connection		Mean heat flow, Btu/(sq ft)(hr)	Interface conductance, Btu/(sq ft)(hr)(°F), at T_m, °F, of -			
	Designation	Type		100	200	300	400
M-13	NAS517 AN363	Screw and nut	15,000 14,000 15,000 14,000	1,713 1,431 2,154 1,698	1,222 1,071 1,510 1,652	863 898 1,085 1,459	630 727 1,028 1,410
N-11-B	P-565-204-100	Exploding rivet	33,000 35,000	102 84	106 99	105 100	----- -----

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1
3
9

W
1
3
9

TABLE V

HEATING HISTORY TESTS FOR SPECIMEN SU-9

[Test interval of 15 minutes with 20-inch-pound torque on screws]

Test	Mean heat flow, Btu/(sq ft)(hr)	Interface conductance, Btu/(sq ft)(hr)(°F) at T_m, °F, of -			
		100	200	300	400
1	8,000	872	628	419	286
2	--do-	774	595	508	459
3	--do-	756	633	490	470
4	--do-	769	558	490	407
5	--do-	720	549	425	365
6	--do-	788	571	467	359
7	--do-	800	523	470	382
8	--do-	872	626	533	435
9	--do-	779	535	467	413
10	9,000	777	538	448	393
11	--do-	834	627	496	423
12	8,000	787	625	471	376
13	9,000	699	545	424	415
14	8,000	640	440	415	297
15	9,000	674	507	394	323
16	8,000	872	630	463	449
17	--do-	726	598	534	319
18	--do-	882	608	565	408
19	--do-	746	597	443	387
20	9,000	844	586	550	340
21	--do-	819	639	528	428
22	--do-	691	605	426	323
23	--do-	663	542	414	343
24	--do-	823	670	502	308
25	--do-	756	635	458	364

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TABLE VI

MEAN AND MEDIAN OF INTERFACE CONDUCTANCE AND

STANDARD DEVIATION FOR SPECIMEN SU-9

[Values based on 25 tests at intervals of 15 minutes]

Mean interface temperature, °F	Interface conductance, Btu/(sq ft)(hr)(°F)		Standard deviation
	Mean	Median	
100	775	777	64.1
200	584	597	51.6
300	472	463	46.4
400	379	382	53.5

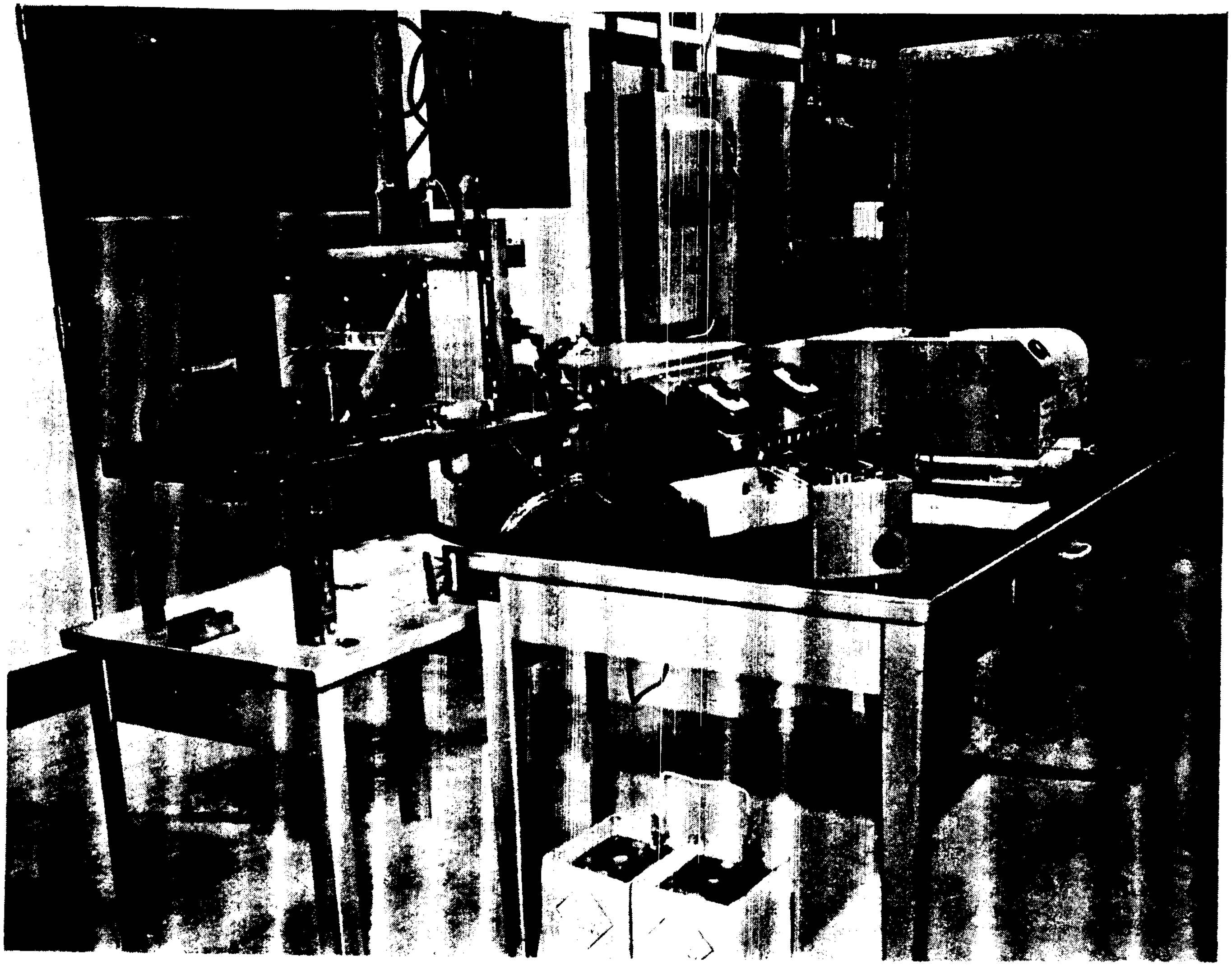

Figure 1.- General view of test apparatus. L-60-262

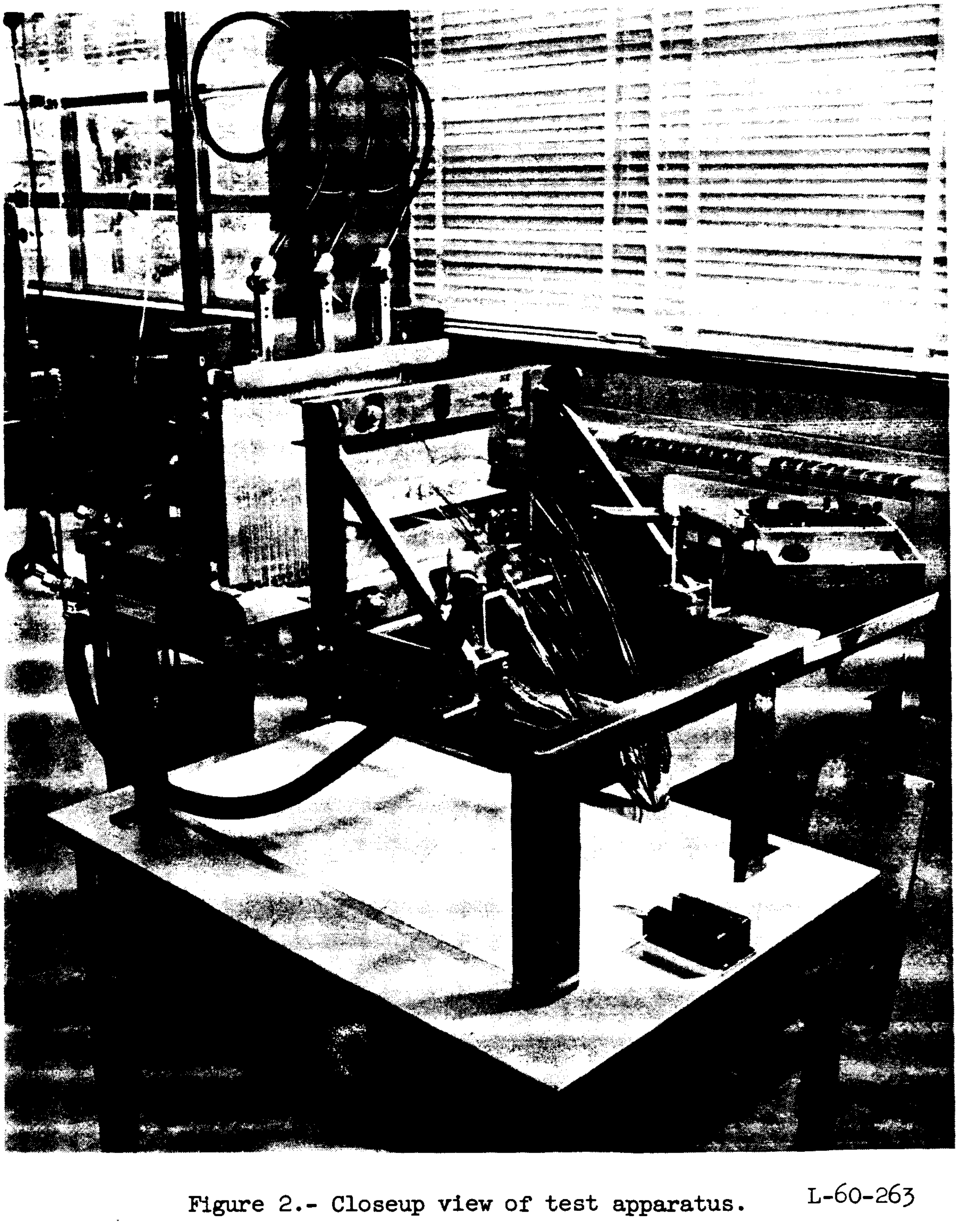

Figure 2.- Closeup view of test apparatus. L-60-263

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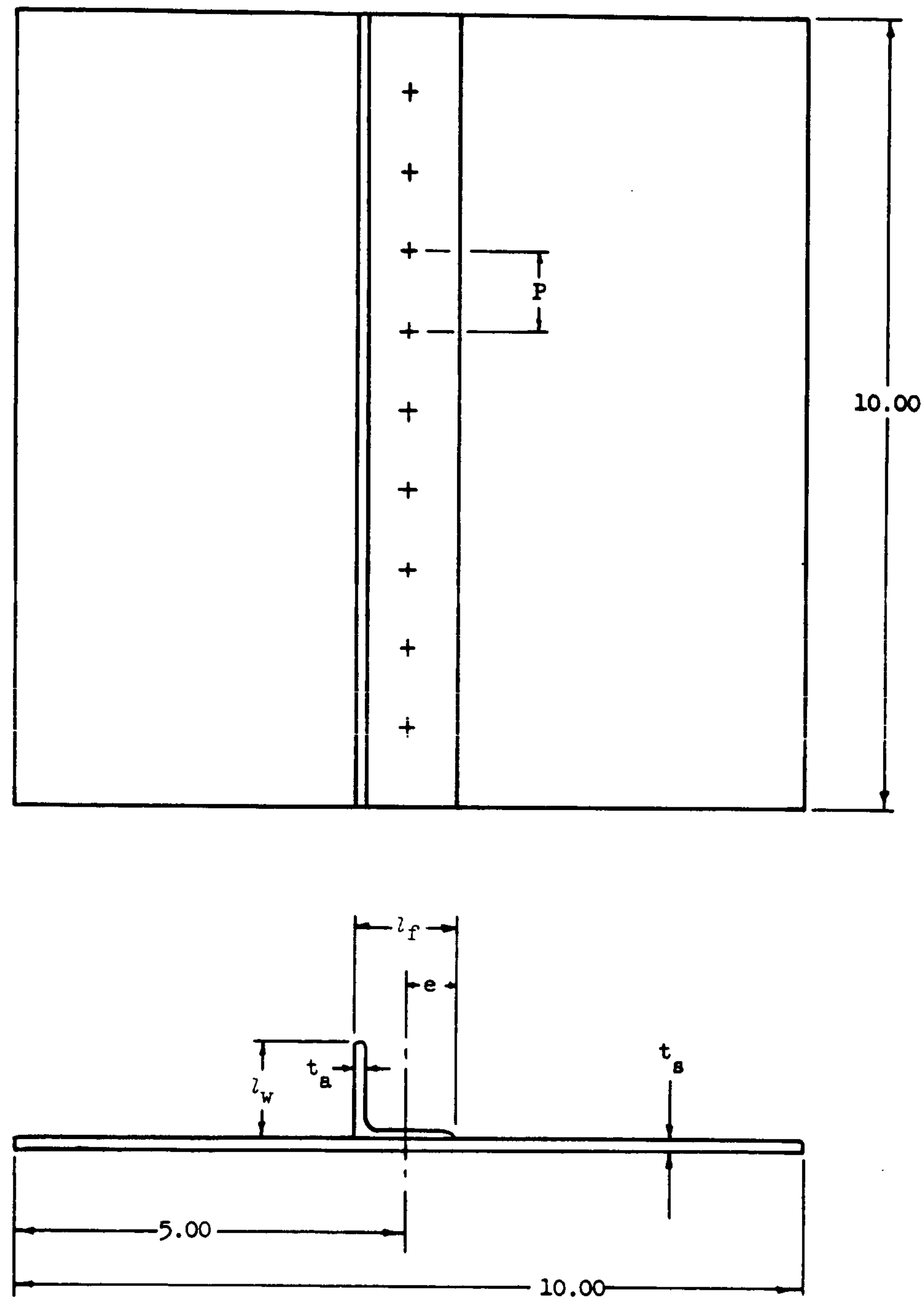
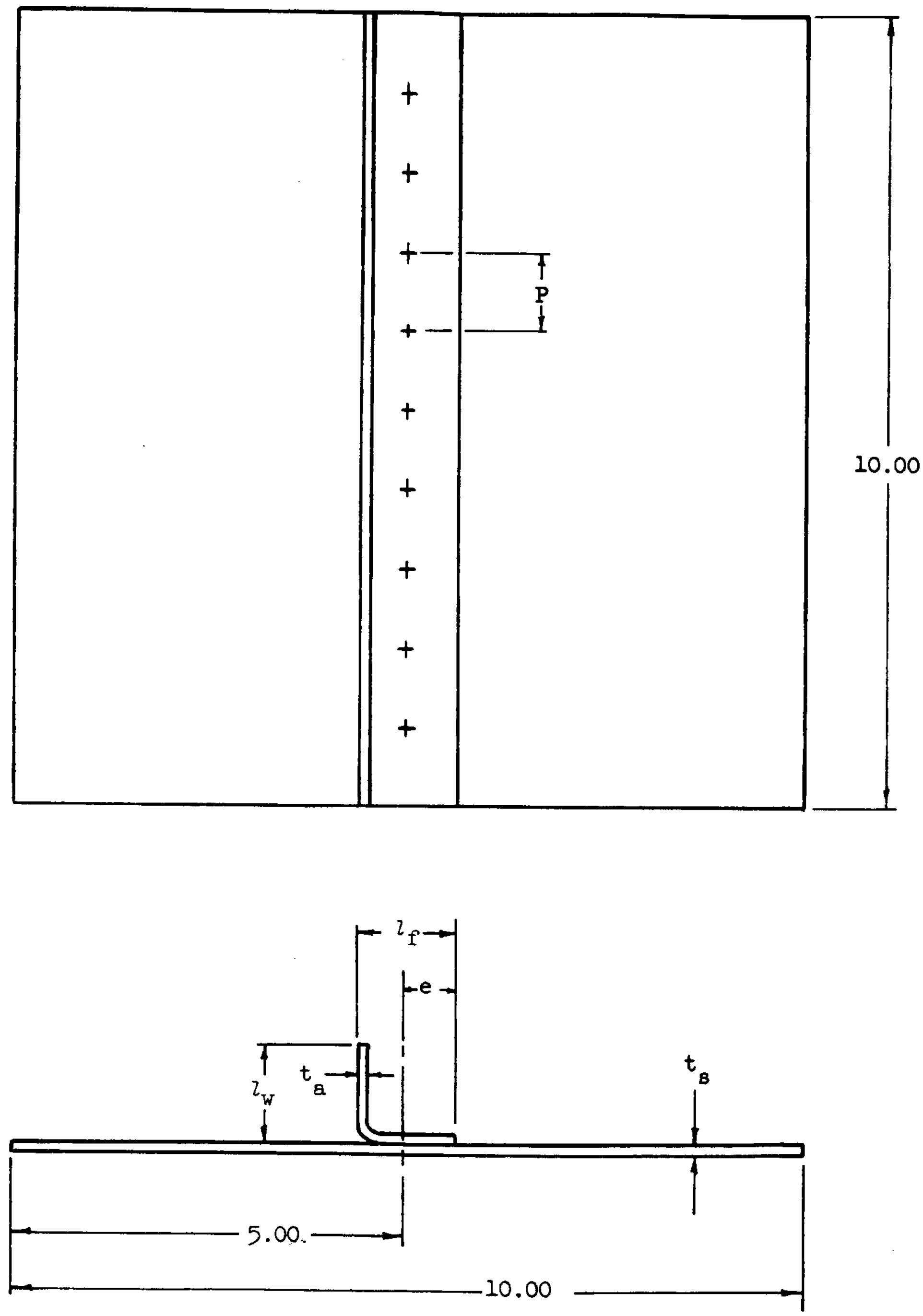


(a) Specimens M-1-A to M-19-B, M-22, N-1-A to N-16, R-1-A to R-10-B, B-2, S-1, SU-1 to SU-12.

Figure 3.- Basic configuration of contact-joint specimens. Dimensions are in inches.



(b) Specimens M-20, M-21, B-1, and B-3.

Figure 3.- Concluded.

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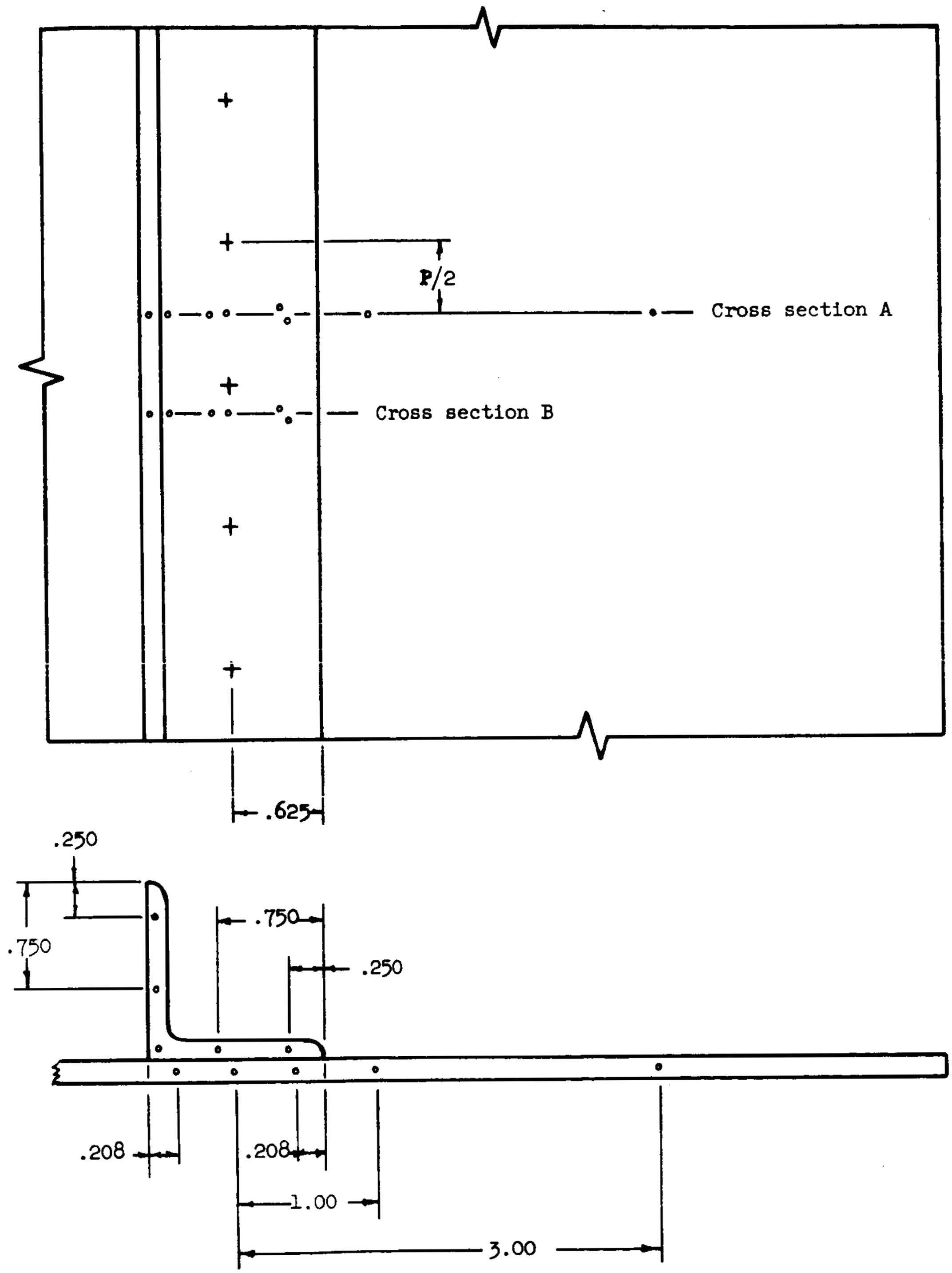
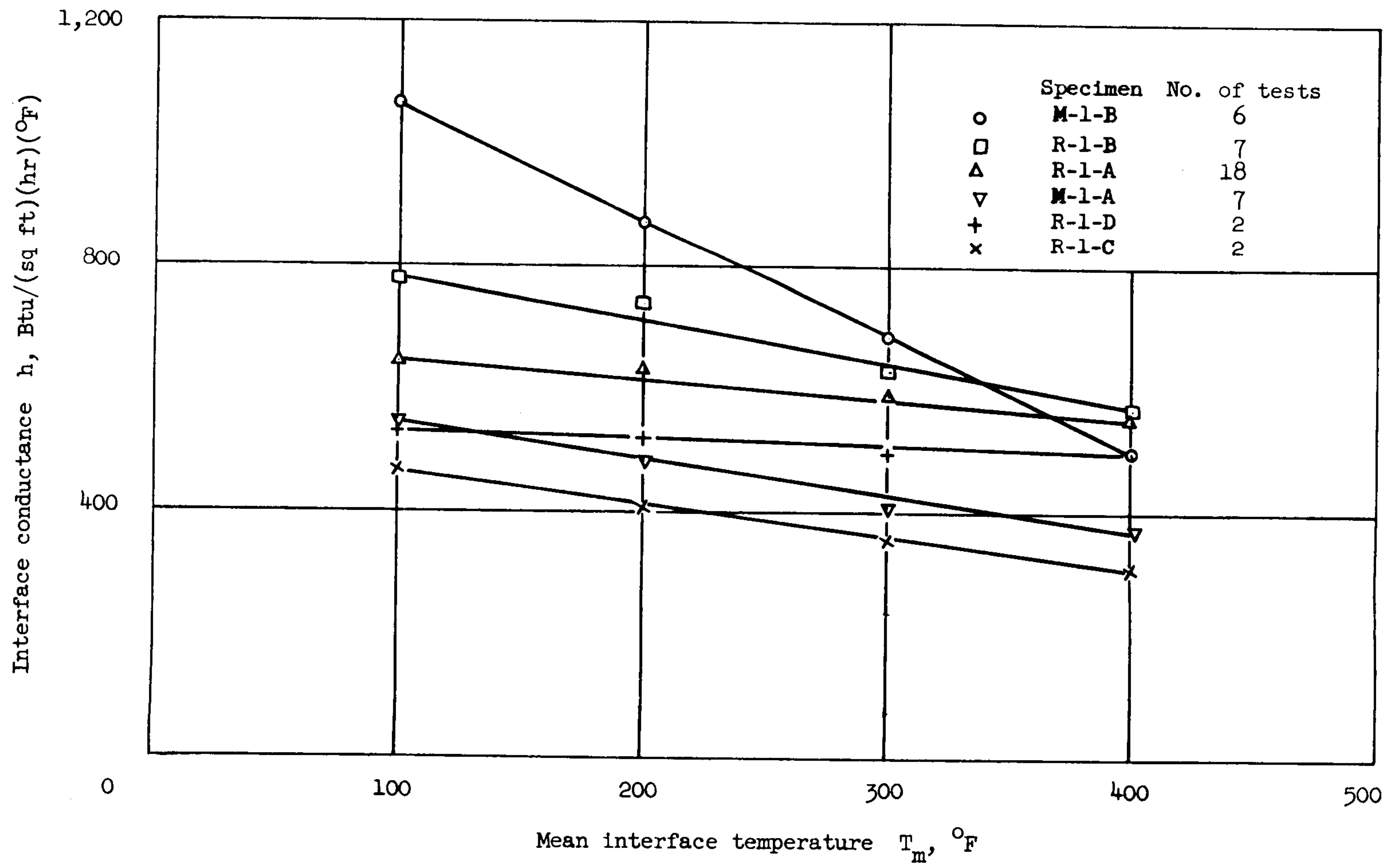
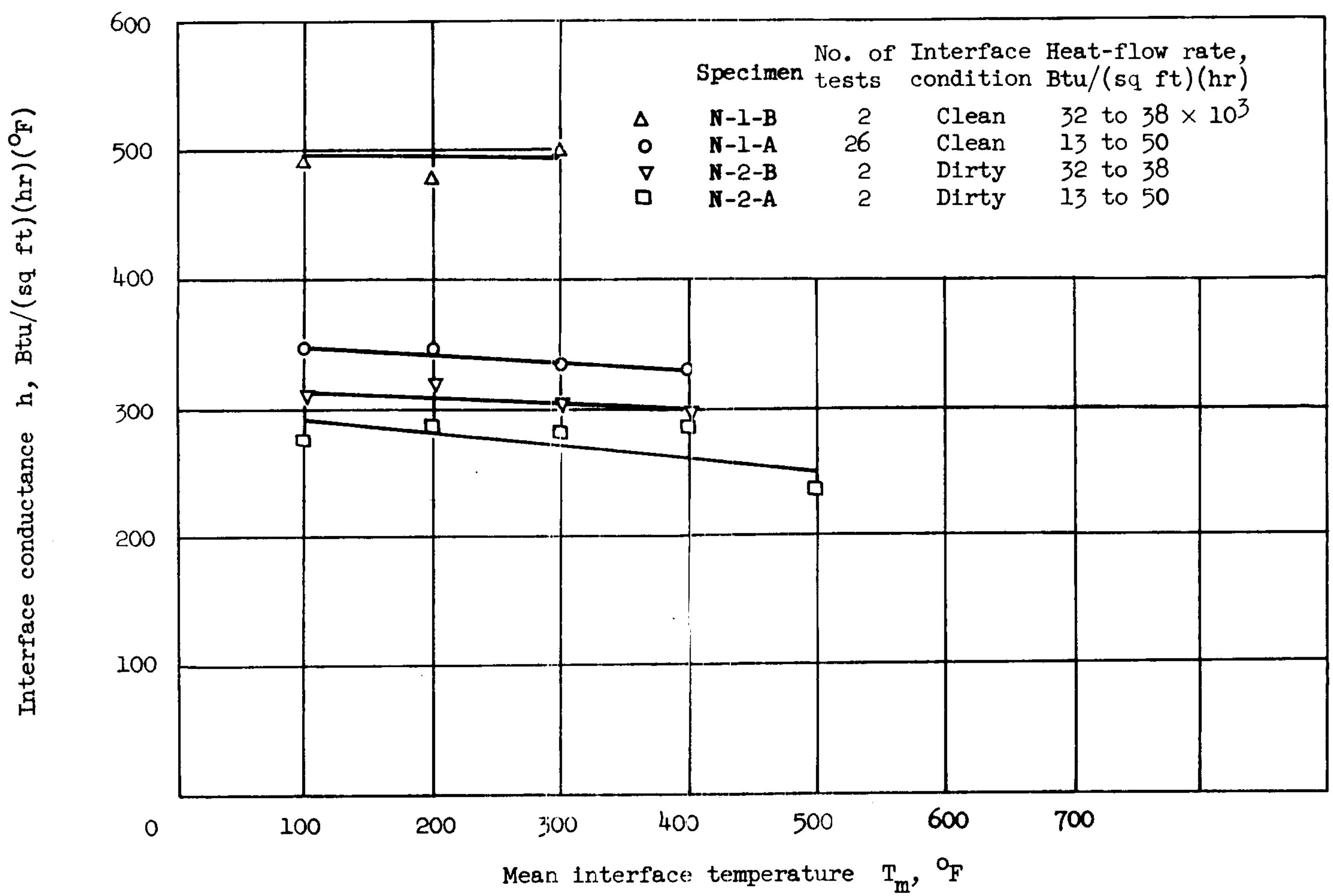


Figure 4.- Thermocouple locations in typical contact-joint specimen. Dimensions are in inches.



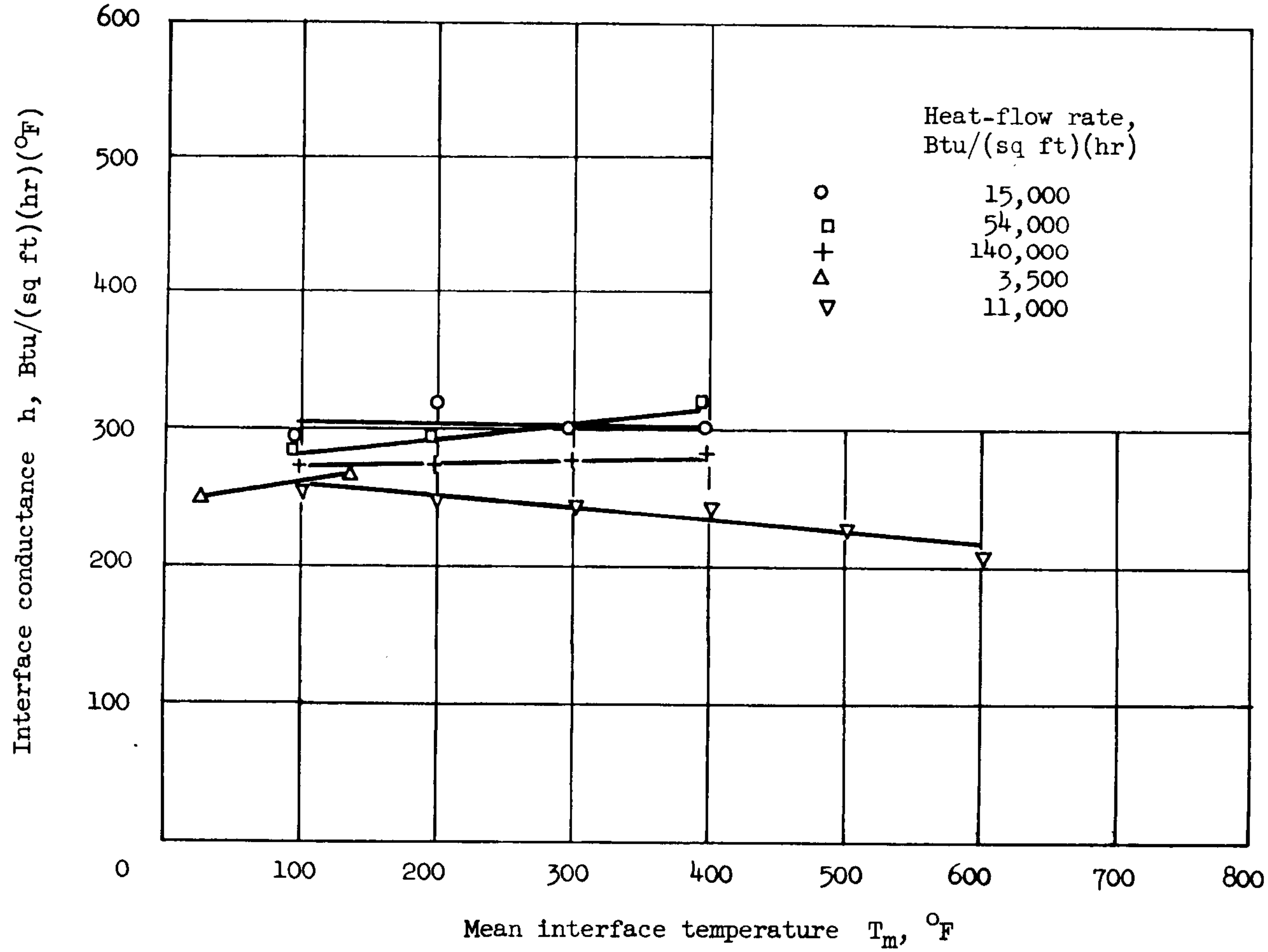
(a) Six geometrically identical specimens with bare and clean interfaces; skin thickness, 0.156 inch; heat-flow rate, 12,000 to 18,000 Btu/(sq ft)(hr); specimens supplied by two different manufacturers.

Figure 5.- Variability of interface conductance with mean interface temperature.



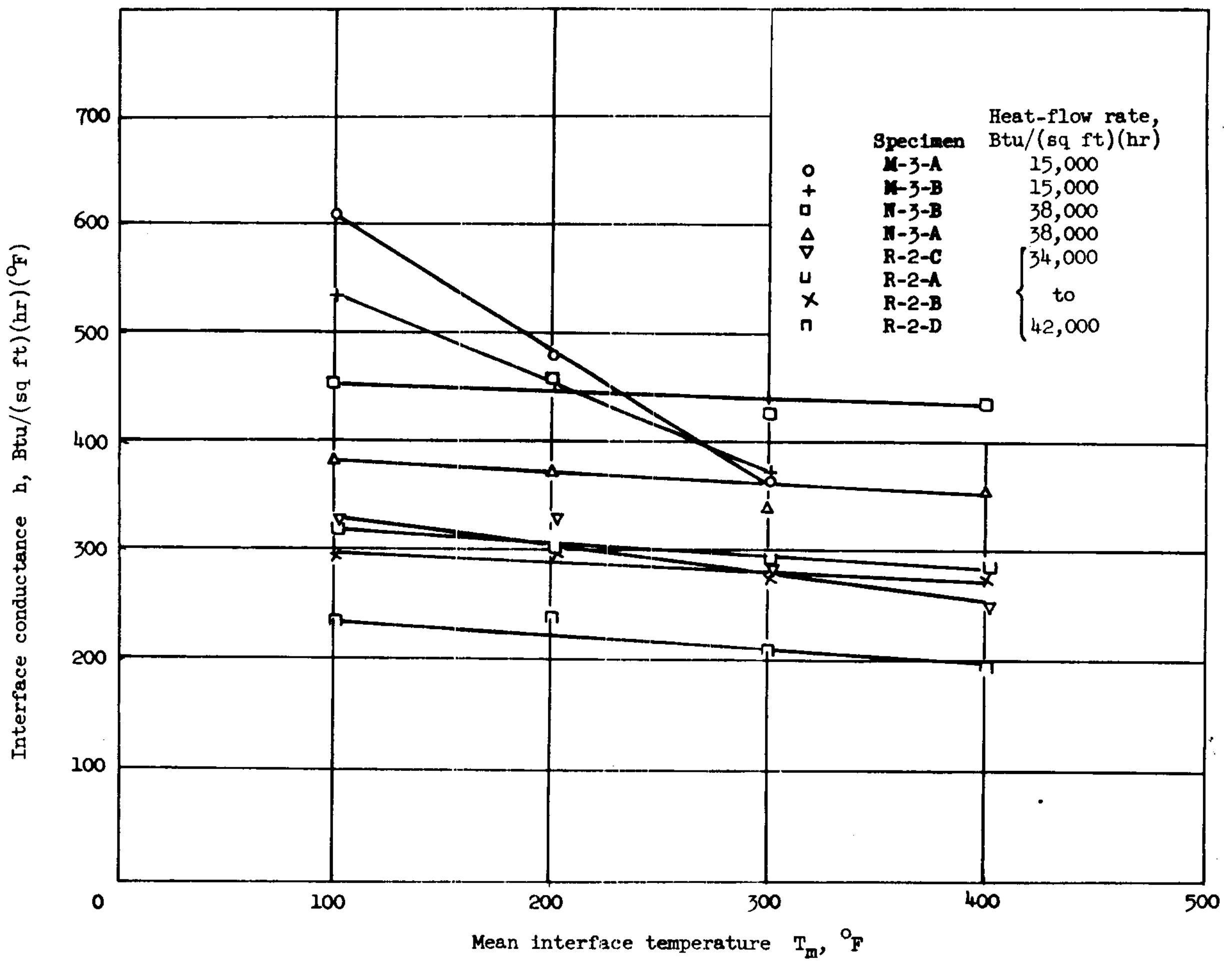
(b) Four geometrically identical specimens with clean or dirty interfaces painted with zinc chromate primer; skin thickness, 0.156 inch; two heat-flow rates; specimens supplied by same manufacturer.

Figure 5.- Continued.



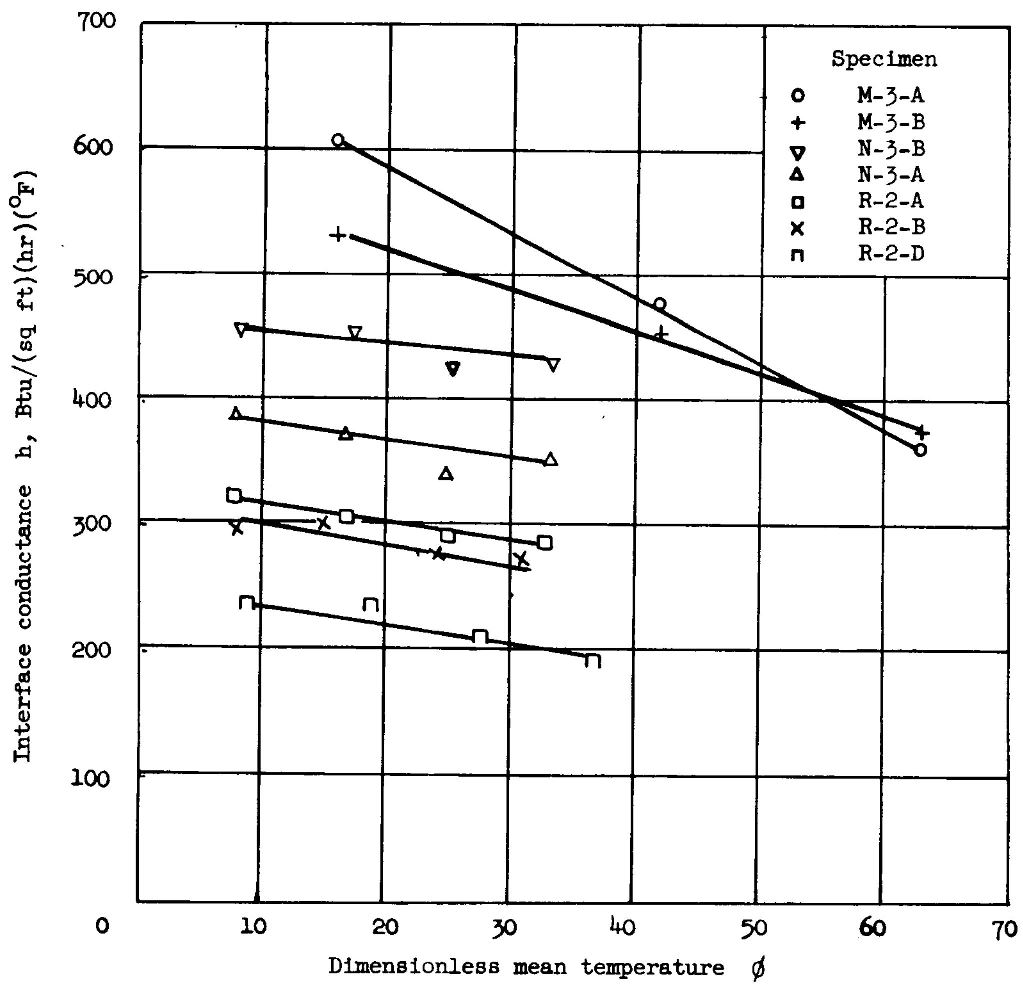
(c) Specimen N-2-A with dirty interface painted with zinc chromate primer; skin thickness, 0.156 inch; several heat-flow rates.

Figure 5.- Continued.



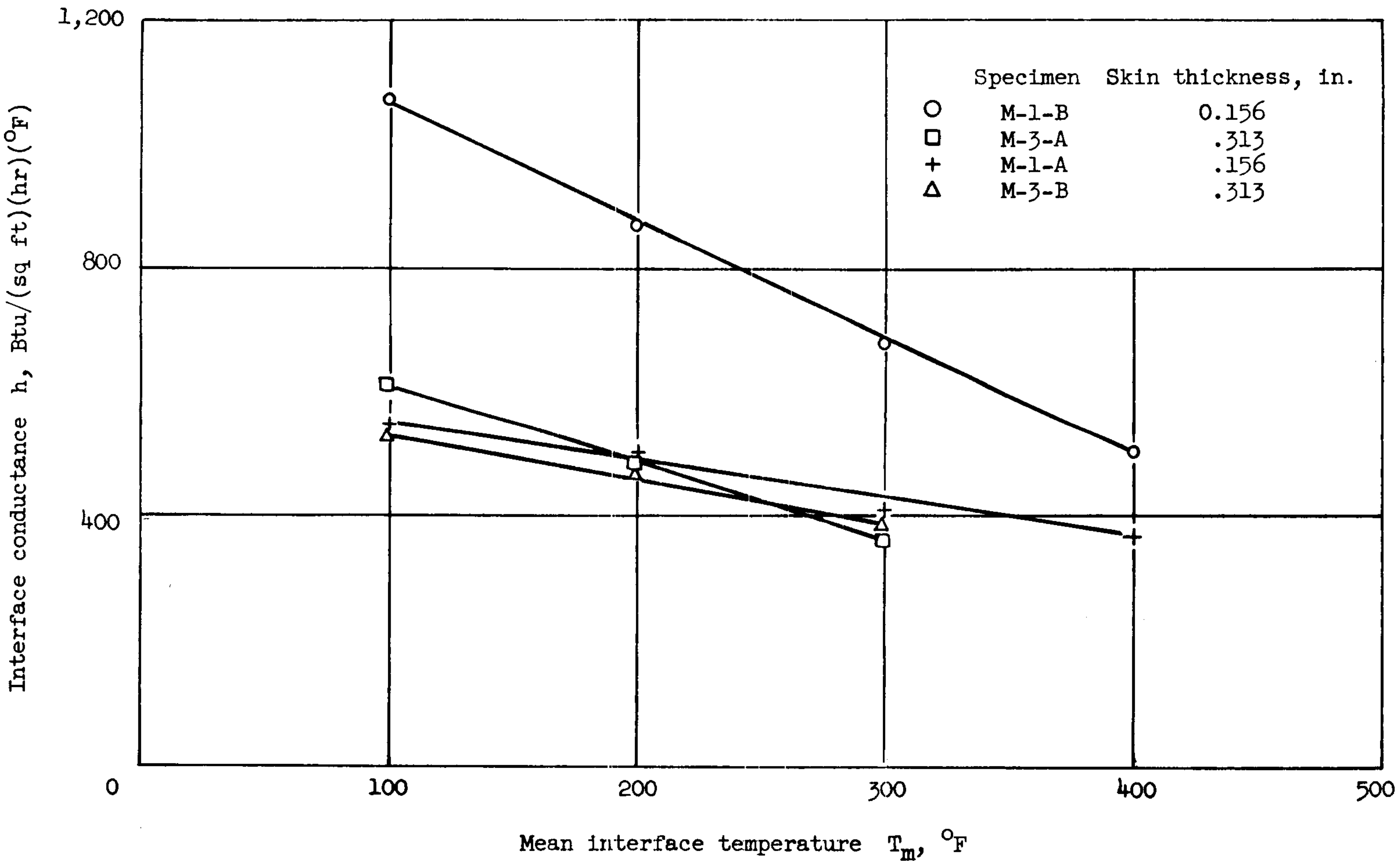
(d) Eight geometrically identical specimens with bare and clean interfaces; skin thickness, 0.313 inch; several heat-flow rates; specimens supplied by three different manufacturers; two tests on each specimen.

Figure 5.- Continued.



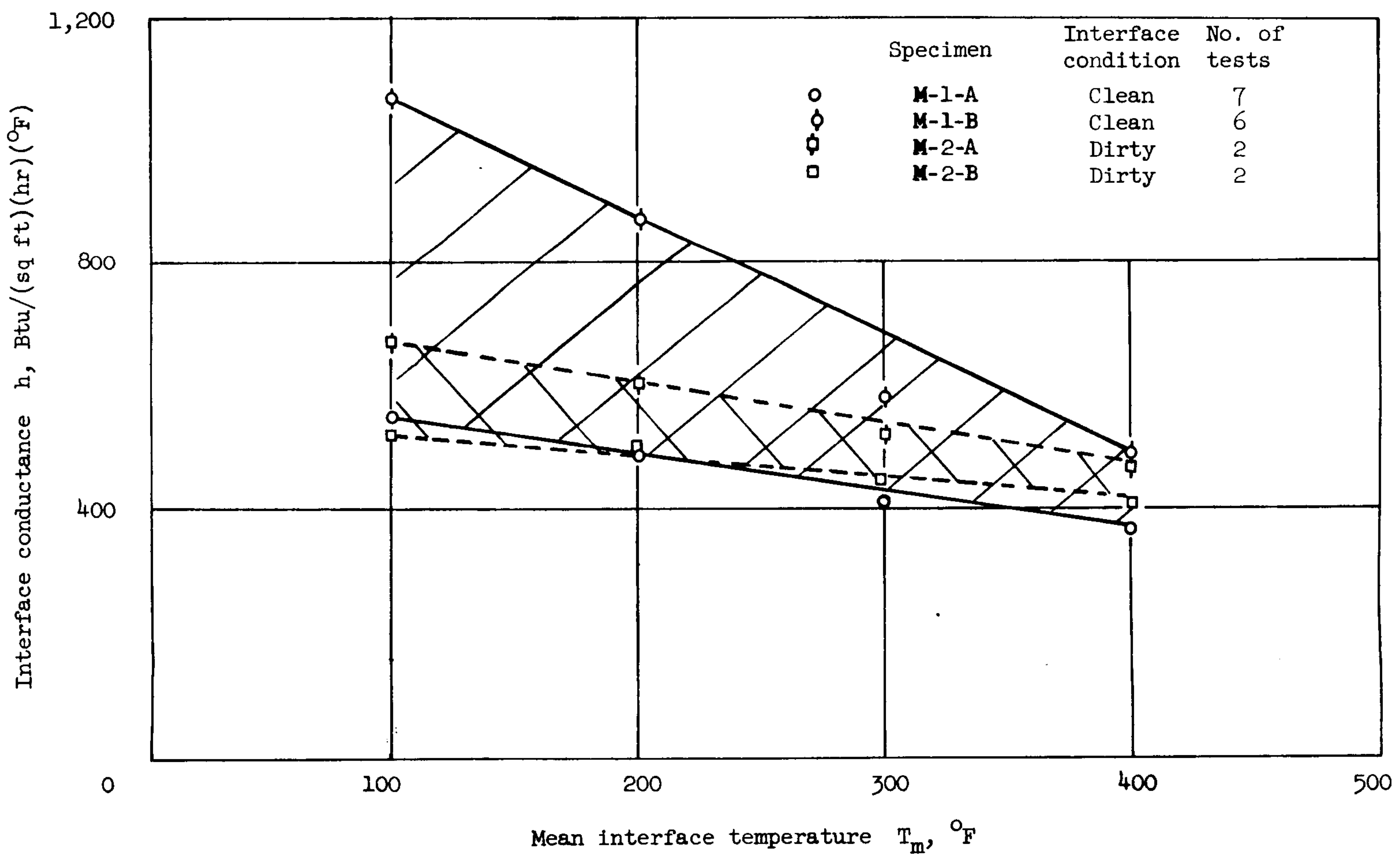
(e) Data in figure 5(d) (with exception of that for one specimen) plotted against dimensionless mean interface temperature ϕ.

Figure 5.- Continued.



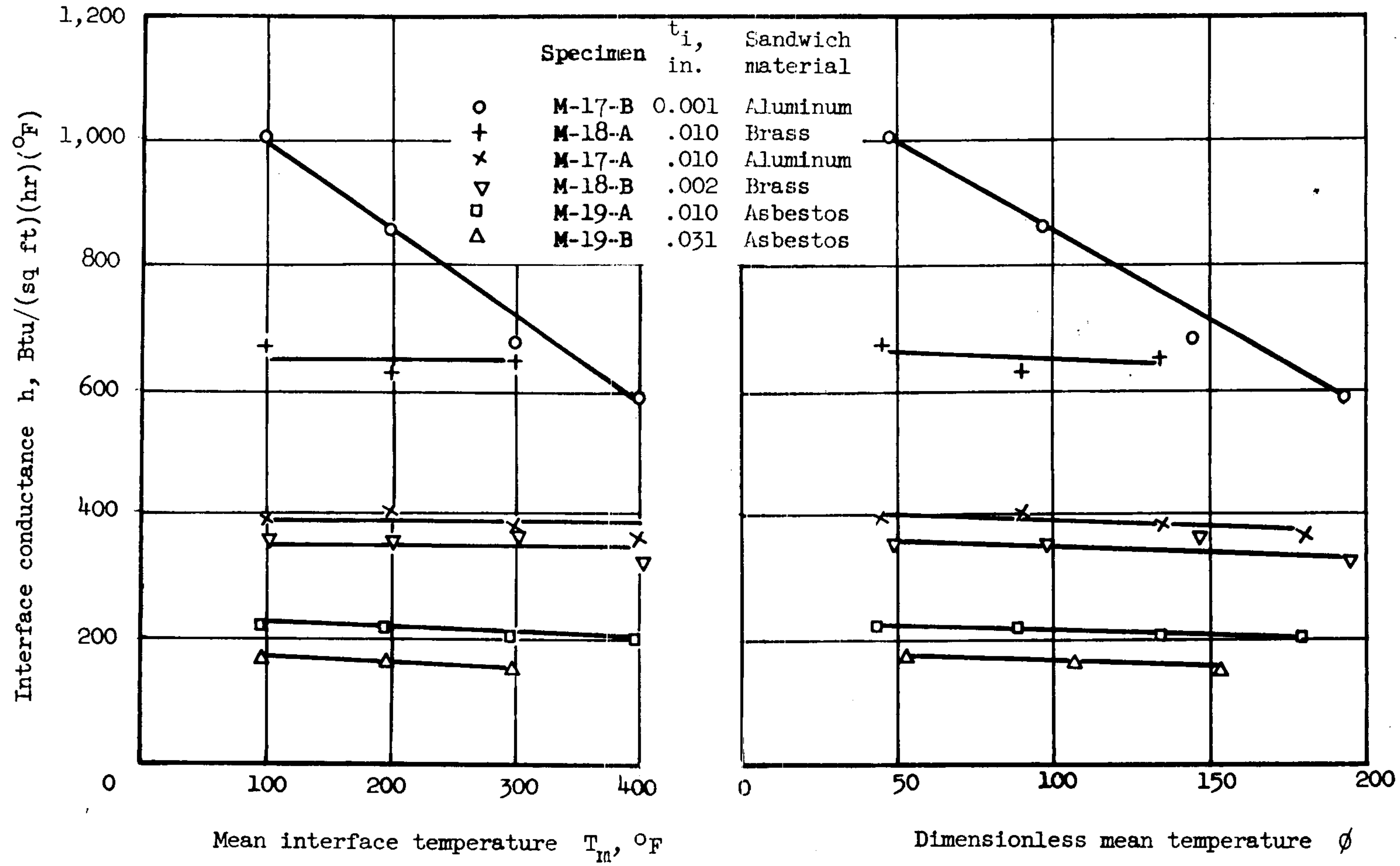
(f) Four specimens with bare and clean interfaces; several skin thicknesses; heat-flow rate, 11,000 to 16,000 Btu/(sq ft)(hr); specimens supplied by same manufacturer.

Figure 5.- Continued.



(g) Four geometrically identical specimens with clean and dirty bare interfaces; skin thickness, 0.156 inch; heat-flow rate, 11,000 to 13,000 Btu/(sq ft)(hr); specimens supplied by same manufacturer. Crosshatching denotes overlap of curves and not additional data within curves.

Figure 5.- Concluded.



(a) Variation with mean interface temperature.

(b) Variation with dimensionless mean temperature.

Figure 6.- Interface conductance of skin-stringer specimens with sandwich materials at interface. Heat-flow rate, 11,000 to 15,000 Btu/(sq ft)(hr).

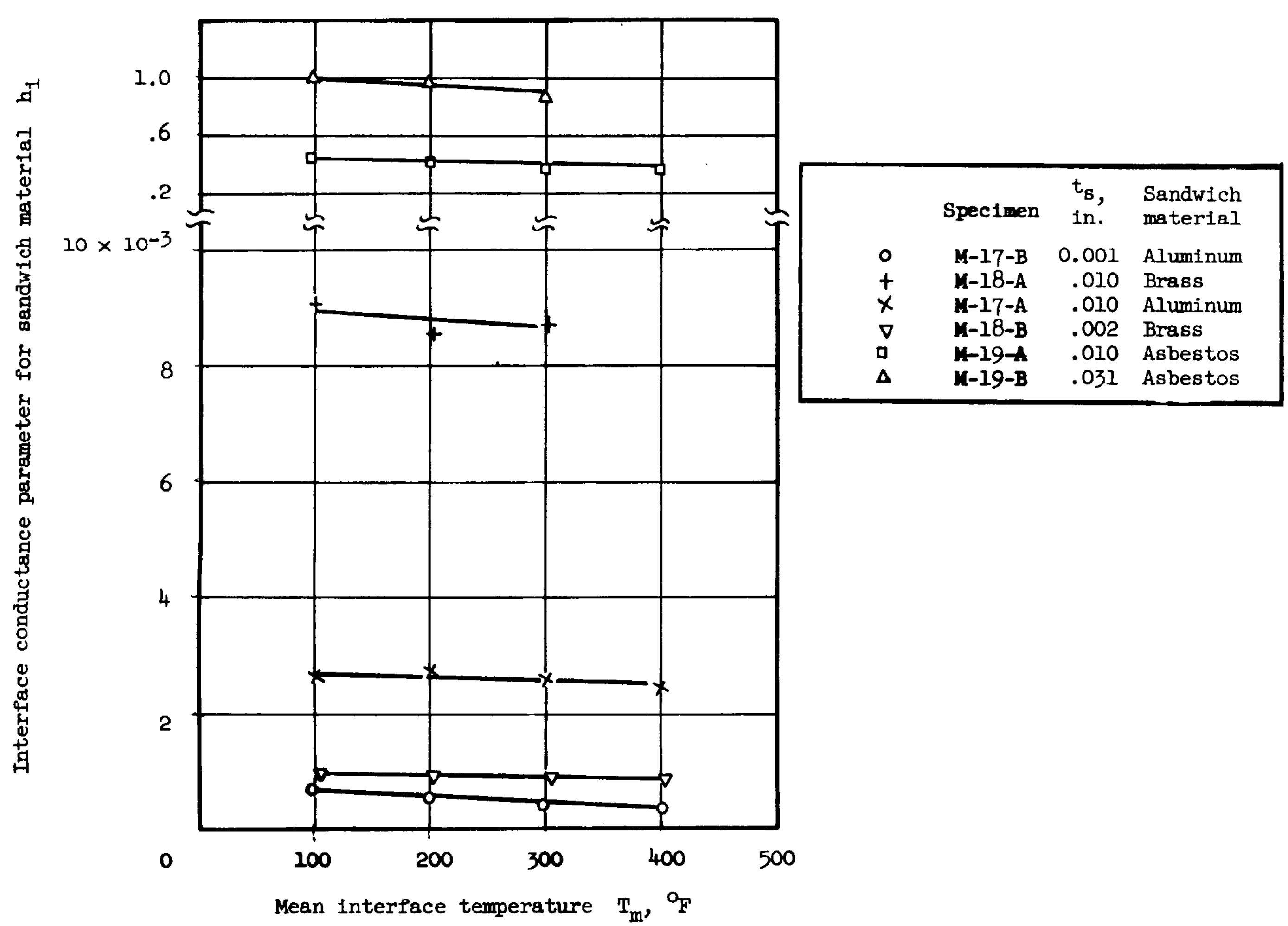


Figure 7.- Variation of interface conductance parameter for sandwich materials with mean interface temperature. Rate of heat flow, 11,000 to 15,000 Btu/(sq ft)(hr); note change in scale of ordinate.

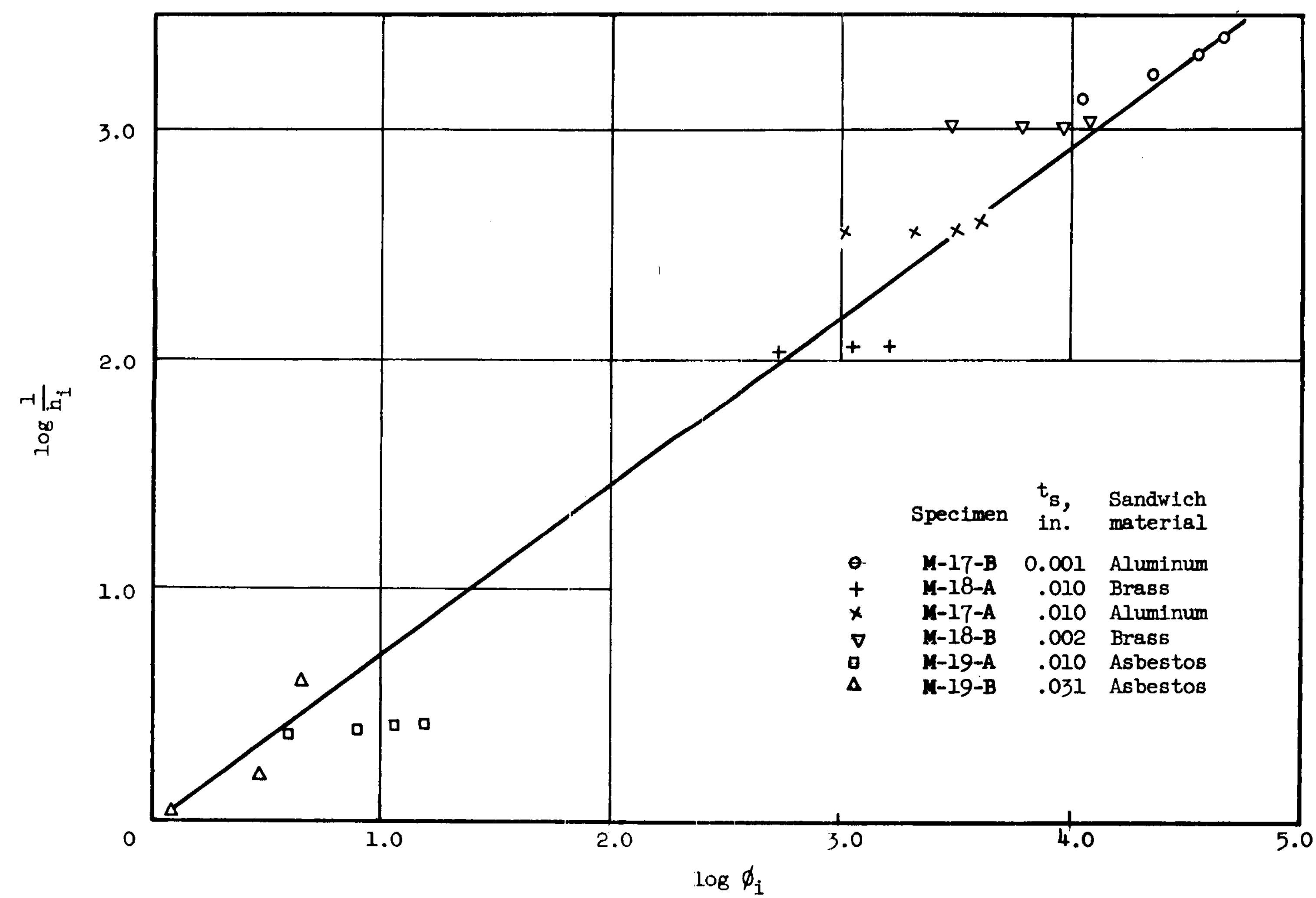
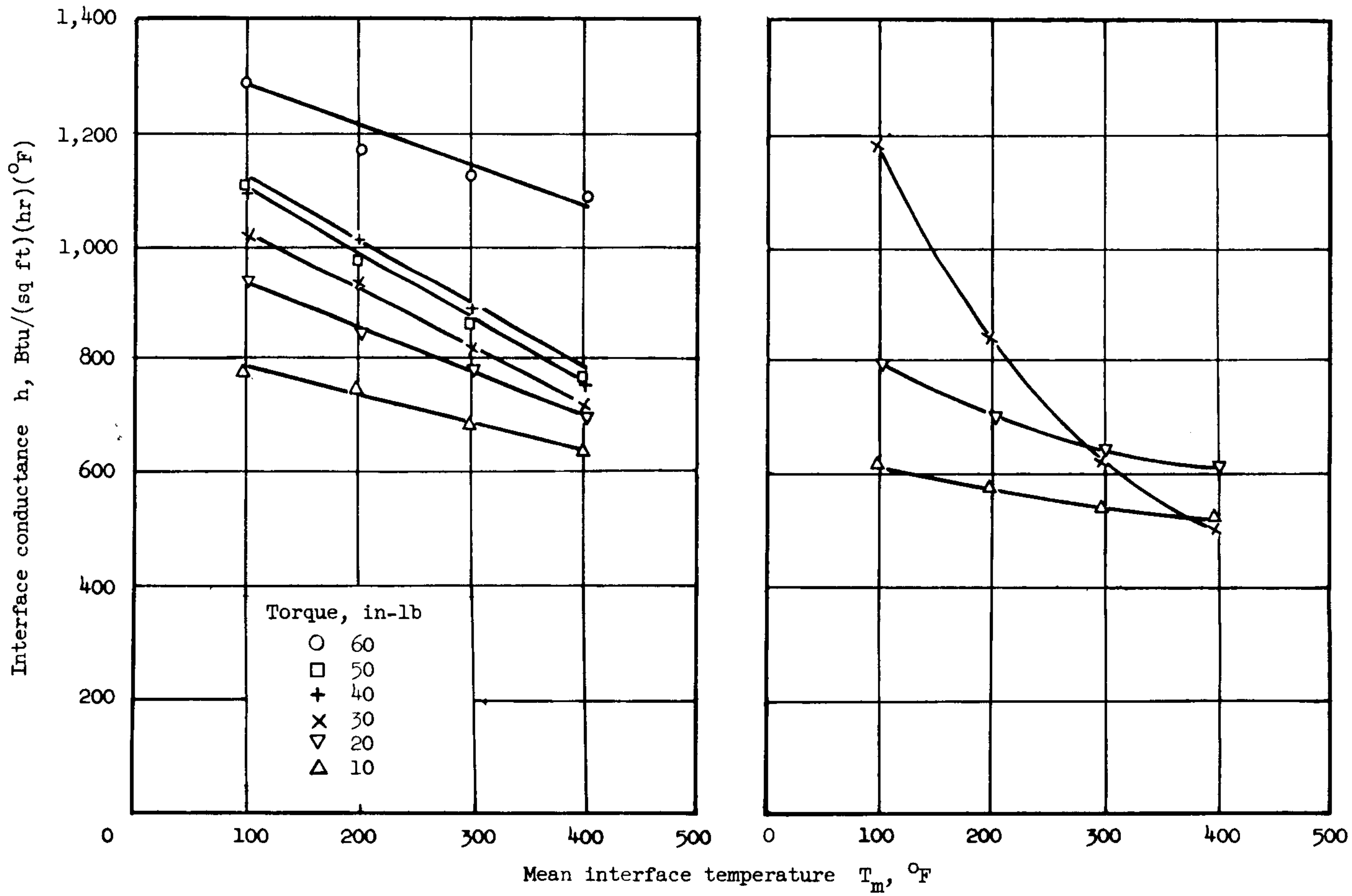


Figure 8.- Plot of $\log \frac{1}{h_i}$ versus $\log \phi_i$ for various sandwich materials. Rate of heat flow, 11,000 to 15,000 Btu/(sq ft)(hr).



(a) Effect of torque; heat-flow rate, 14,000 to 16,000 Btu/(sq ft)(hr); steel screws.

(b) Effect of torque; heat-flow rate, 14,000 to 16,000 Btu/(sq ft)(hr); aluminum screws.

Figure 9.- Data for specimen M-15 plotted to show effect of heat-flow rate and torque on screws on interface conductance at various mean interface temperatures. Interface bare and clean.

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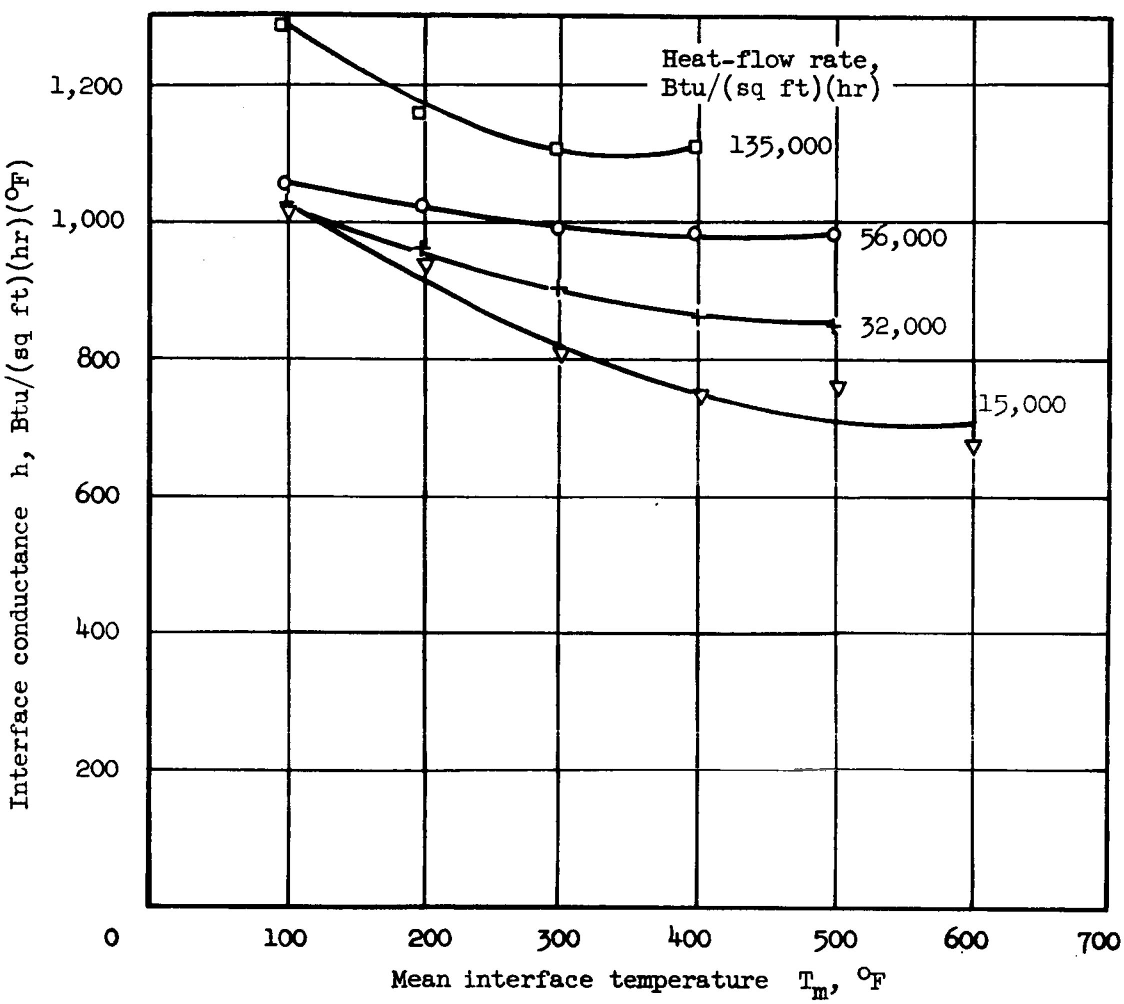
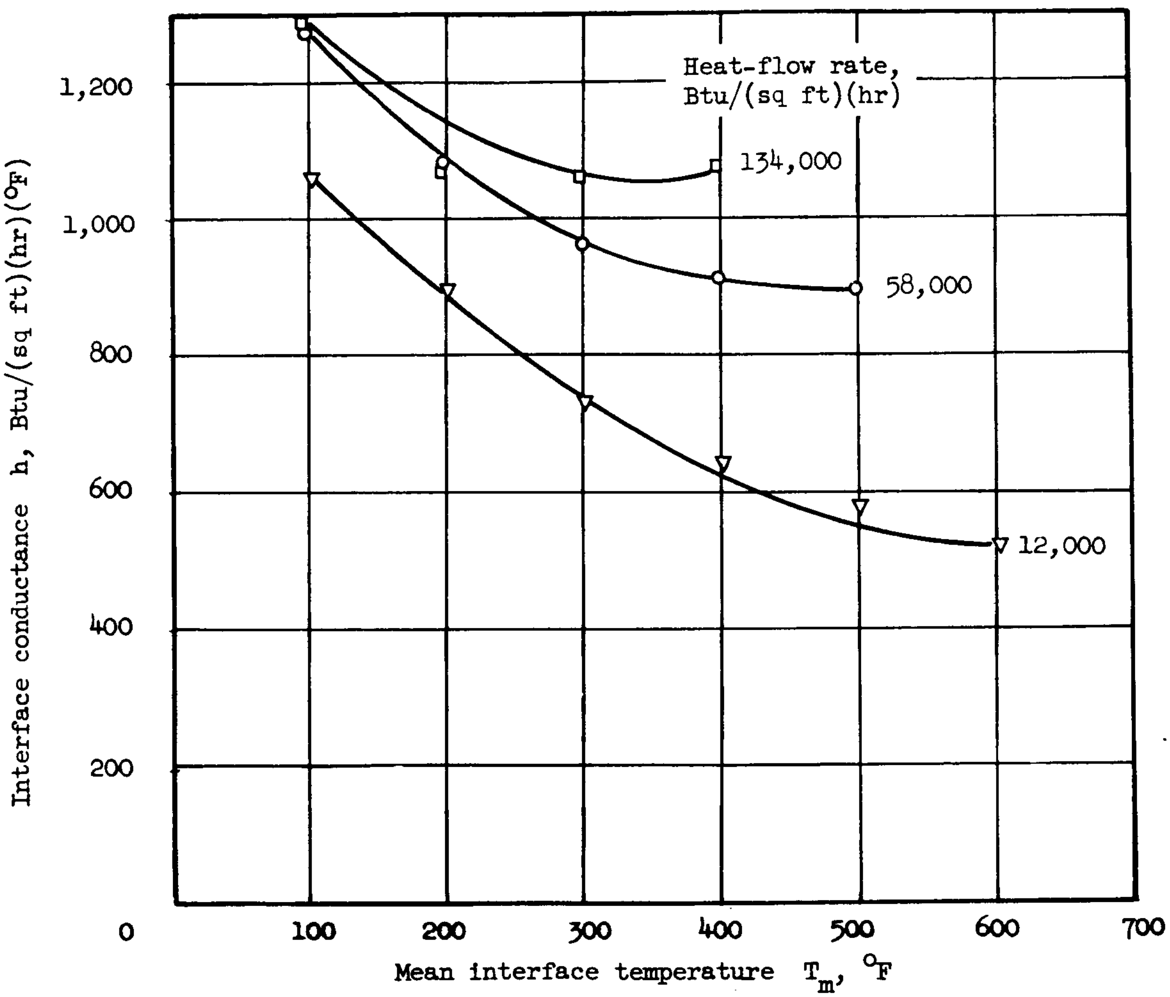


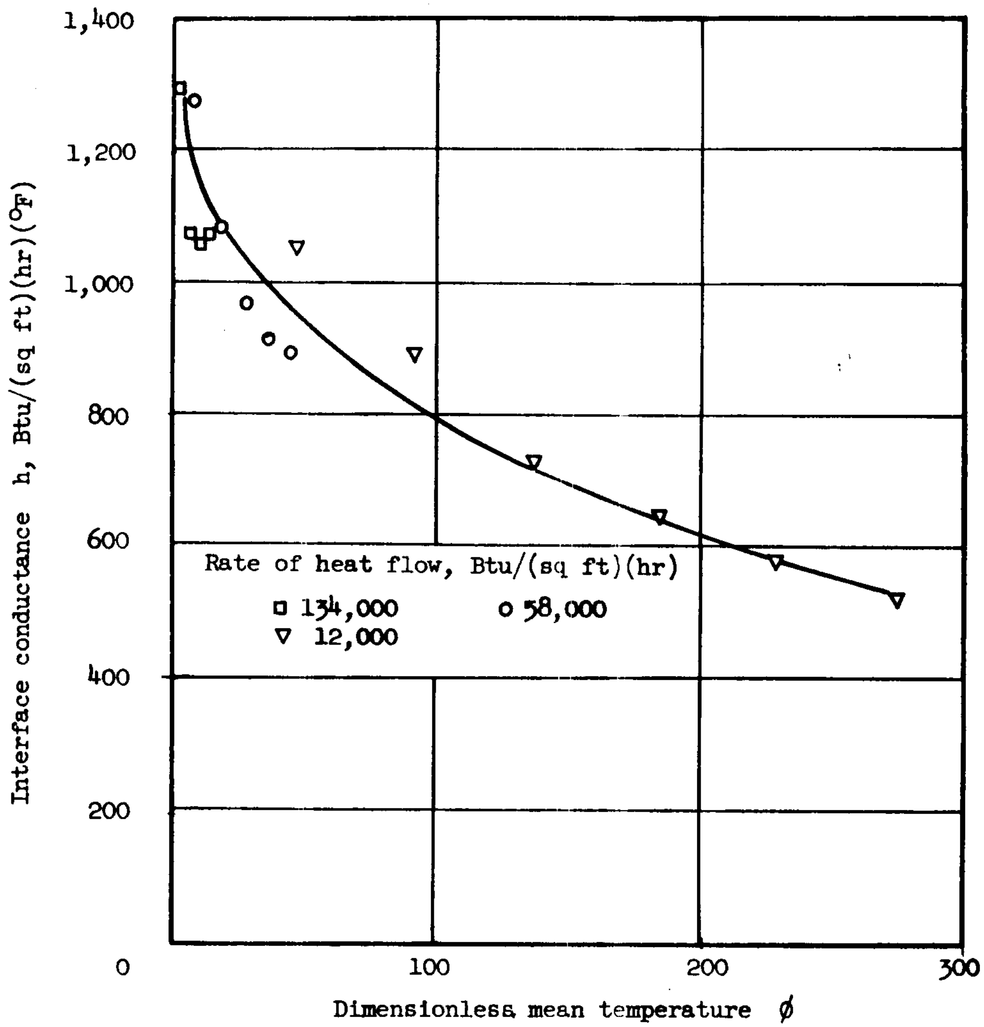
(c) Effect of heat-flow rate; torque, 30 inch-pounds; steel screws.

Figure 9.- Continued.



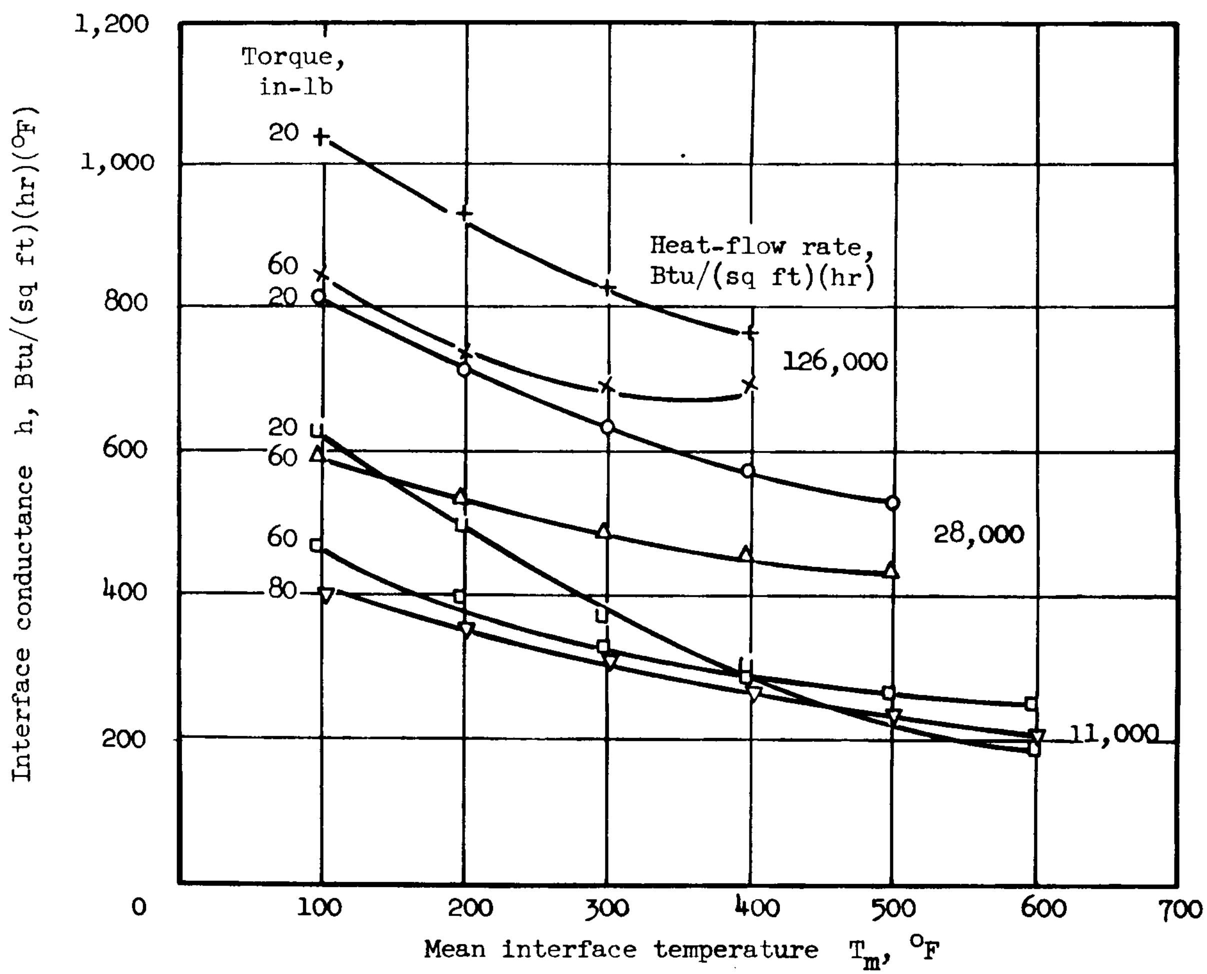
(d) Effect of heat-flow rate; torque, 60 inch-pounds; steel screws.

Figure 9.- Continued.



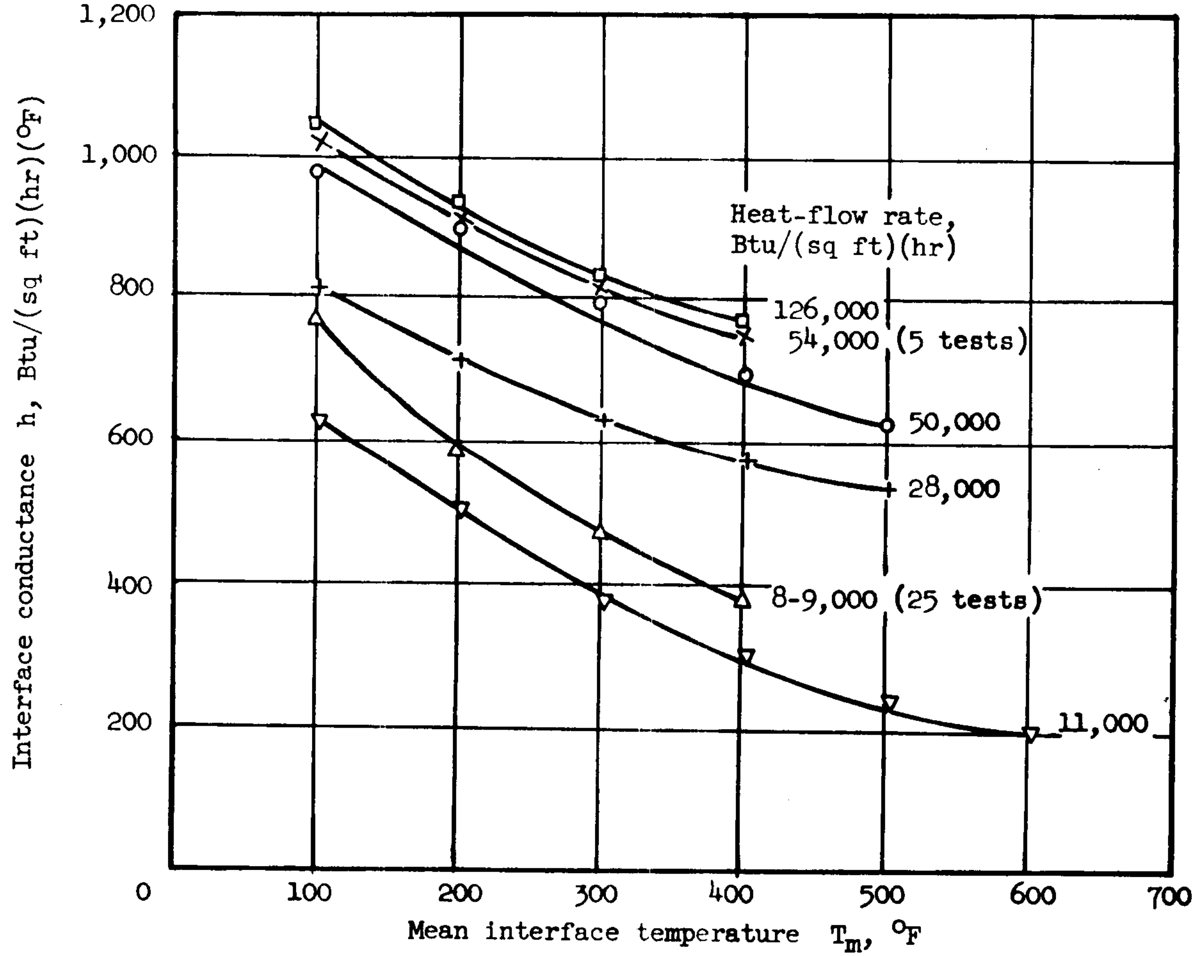
(e) Data in figure 9(d) plotted against dimensionless mean interface temperature.

Figure 9.- Concluded.



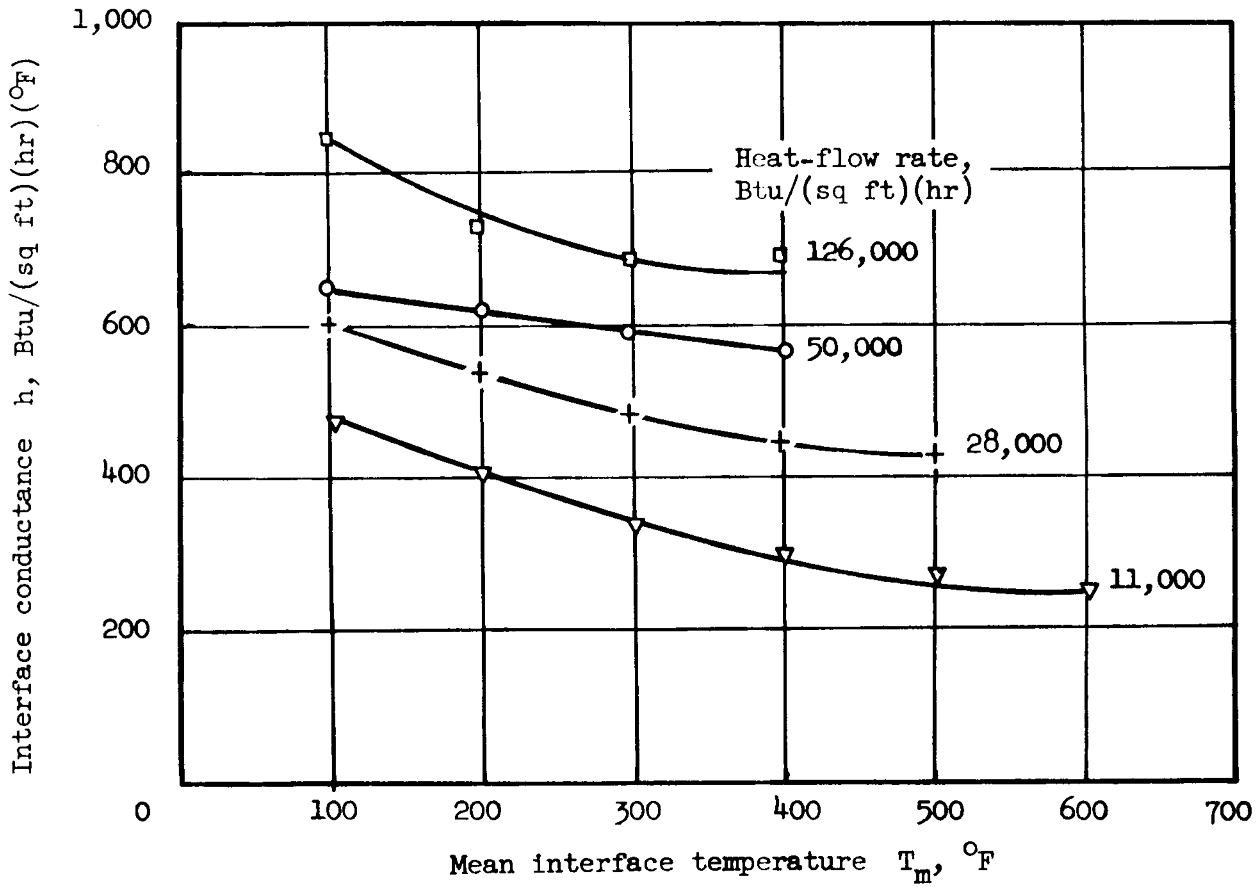
(a) Effect of screw torque at three different heat-flow rates.

Figure 10.- Data for specimen SU-9 plotted to show effects of pressure and heat-flow rate on interface conductance at several mean interface temperatures. Interface bare and clean; steel screws.



(b) Effect of heat-flow rate; torque, 20 inch-pounds. All data are for a single test unless otherwise specified.

Figure 10.- Continued.



(c) Effect of heat-flow rate; torque, 60 inch-pounds.

Figure 10.- Concluded.

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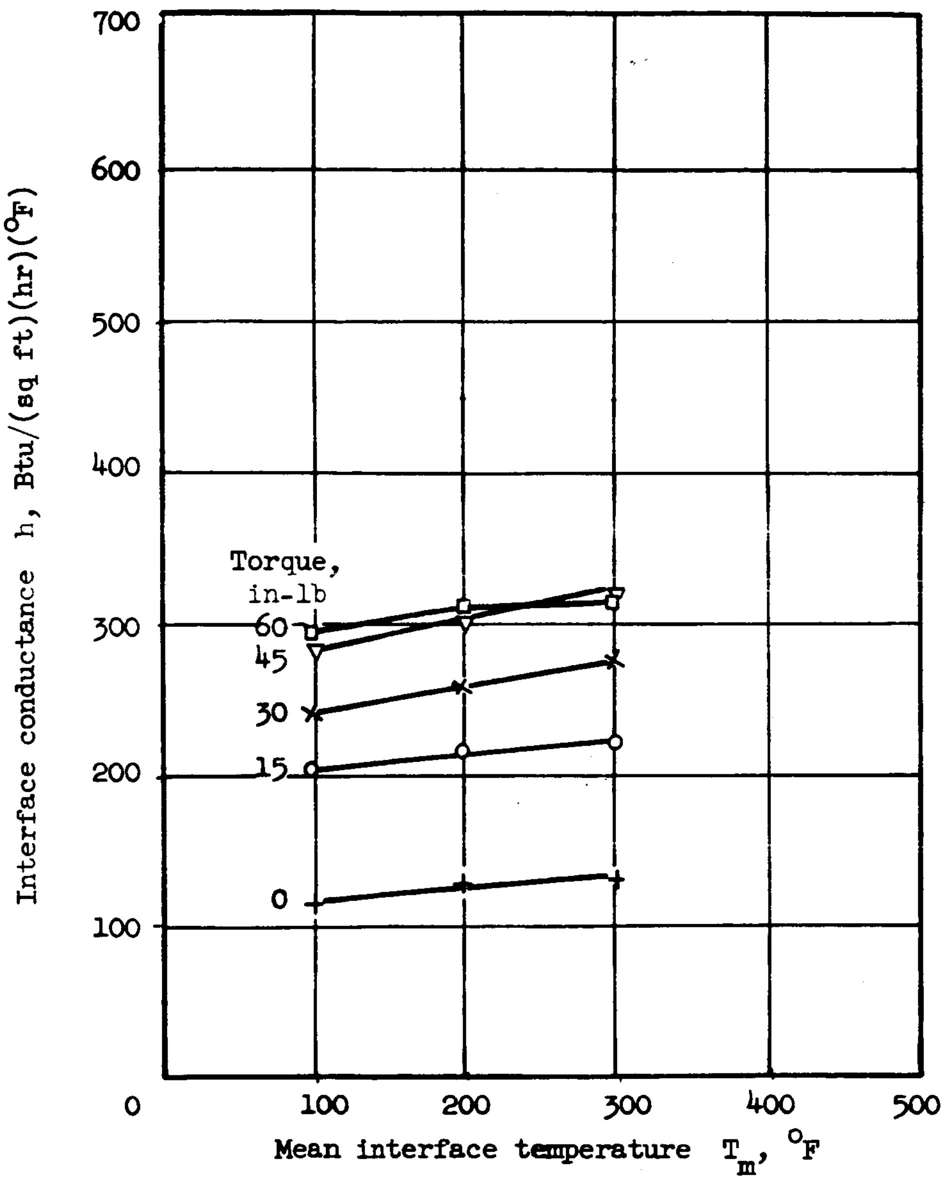

Figure 11.- Data for specimen S-1 plotted to show effect of screw torque on interface conductance at various mean interface temperatures. Steel screws and fiber insert nuts; interface painted with zinc chromate; rate of heat flow, 31,000 to 34,000 Btu/(sq ft)(hr).

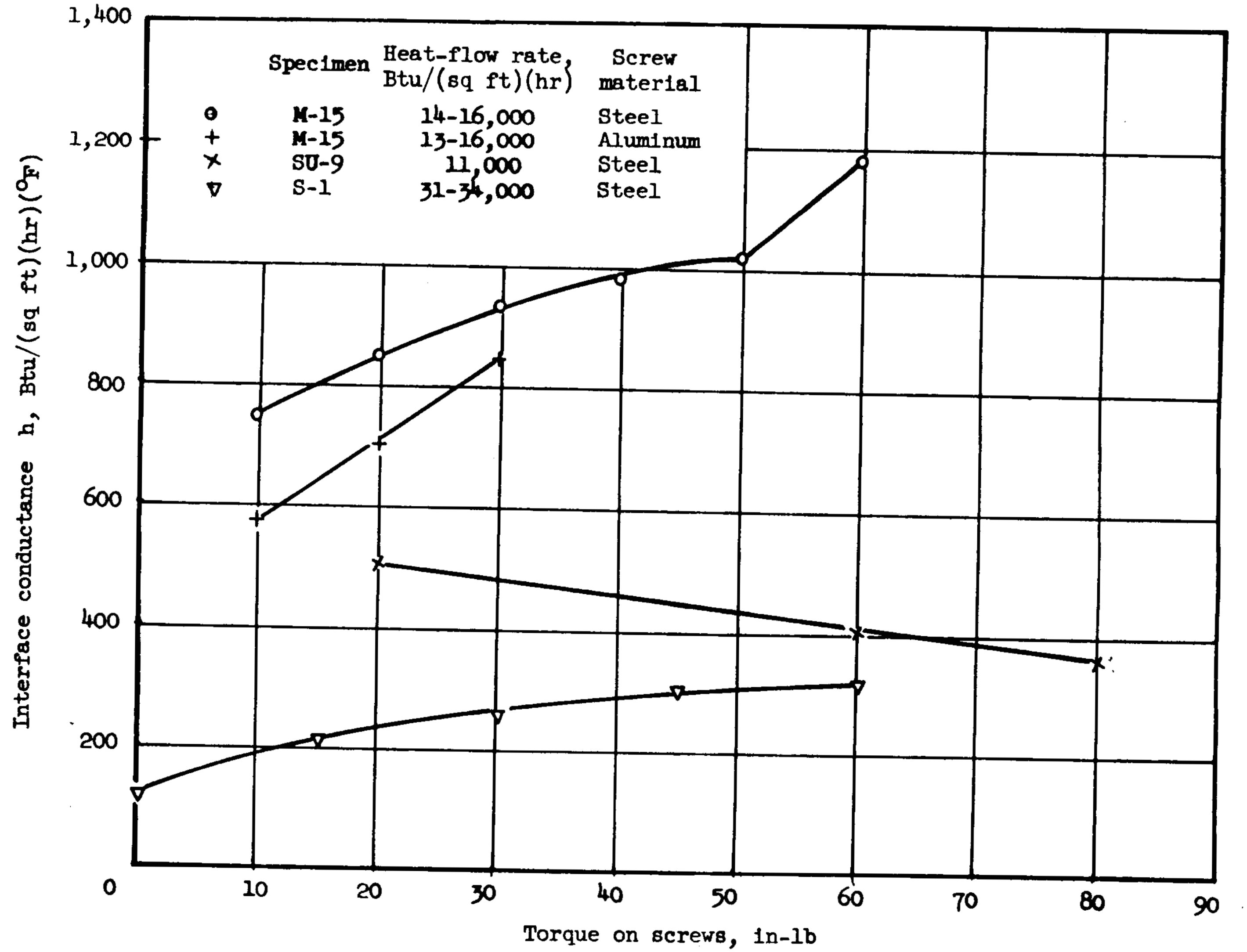

Figure 12.- Effect of screw torque on interface conductance for specimens M-15, SU-9, and S-1 at same mean interface temperature.

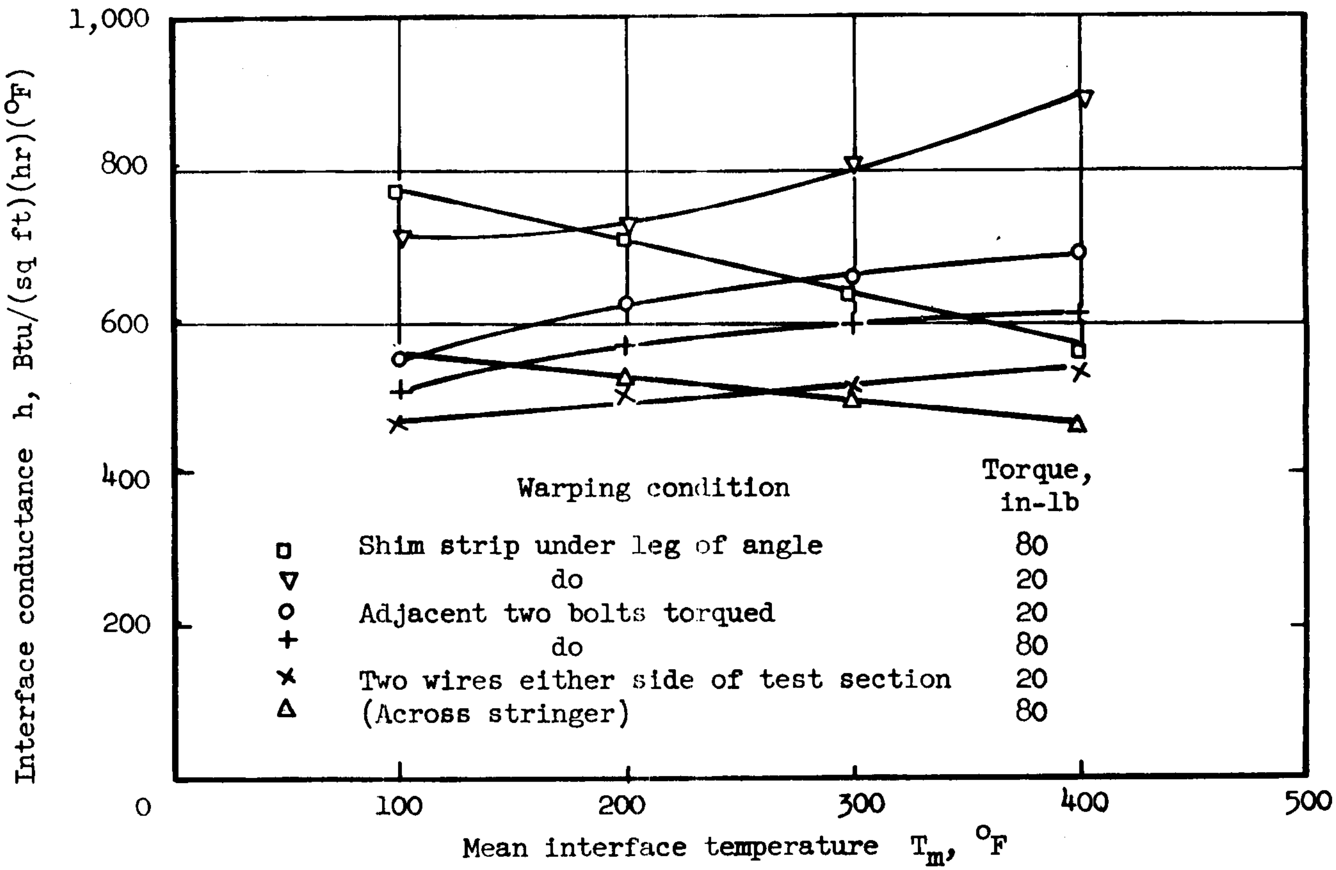

Figure 13.- Effect of induced warping of specimen SU-9 on interface conductance at various mean interface temperatures. Interface bare and clean; steel screws.

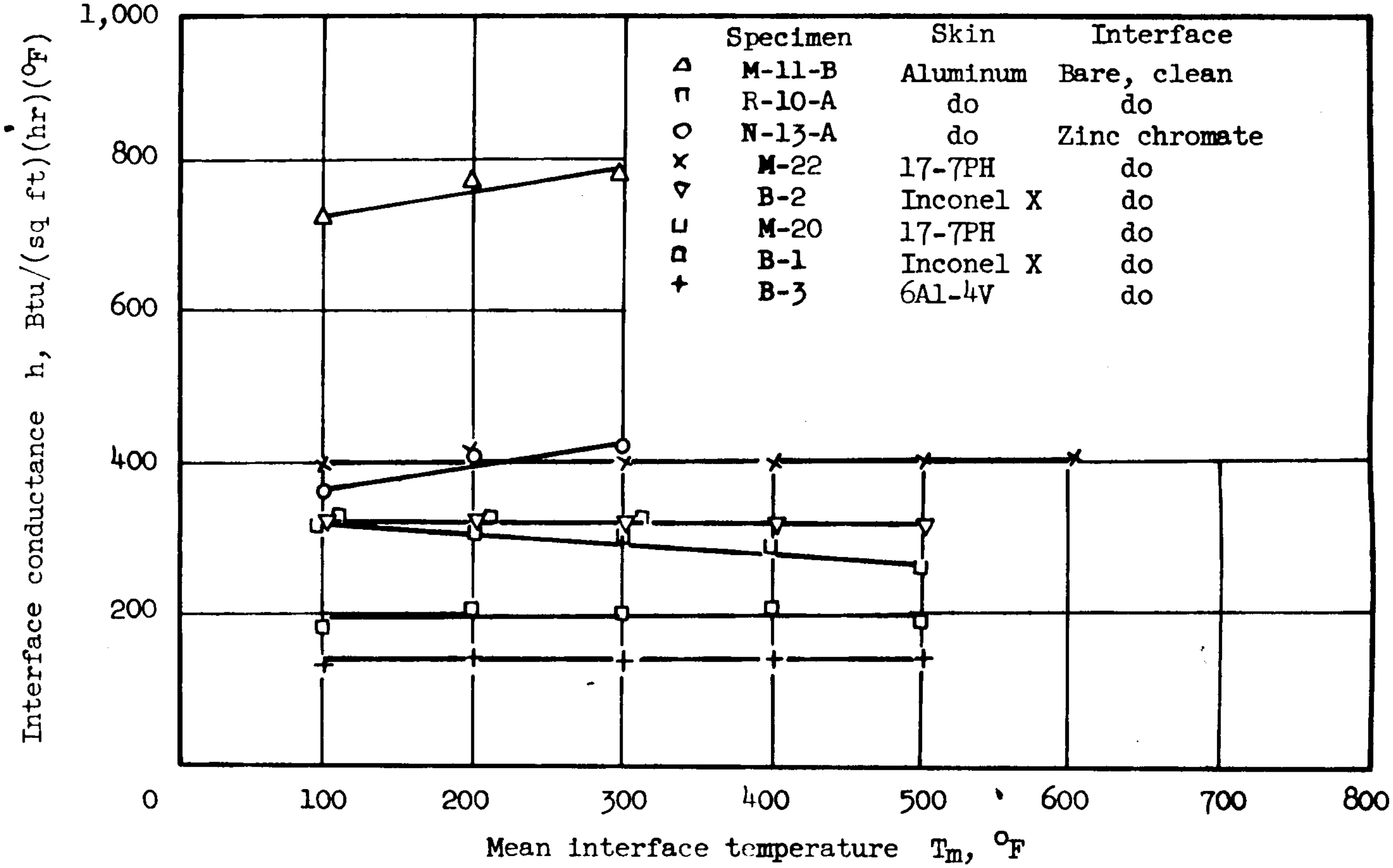

Figure 14.- Comparison of interface conductance values for combinations of various skin materials with aluminum stringers. Monel rivets used for all specimens.

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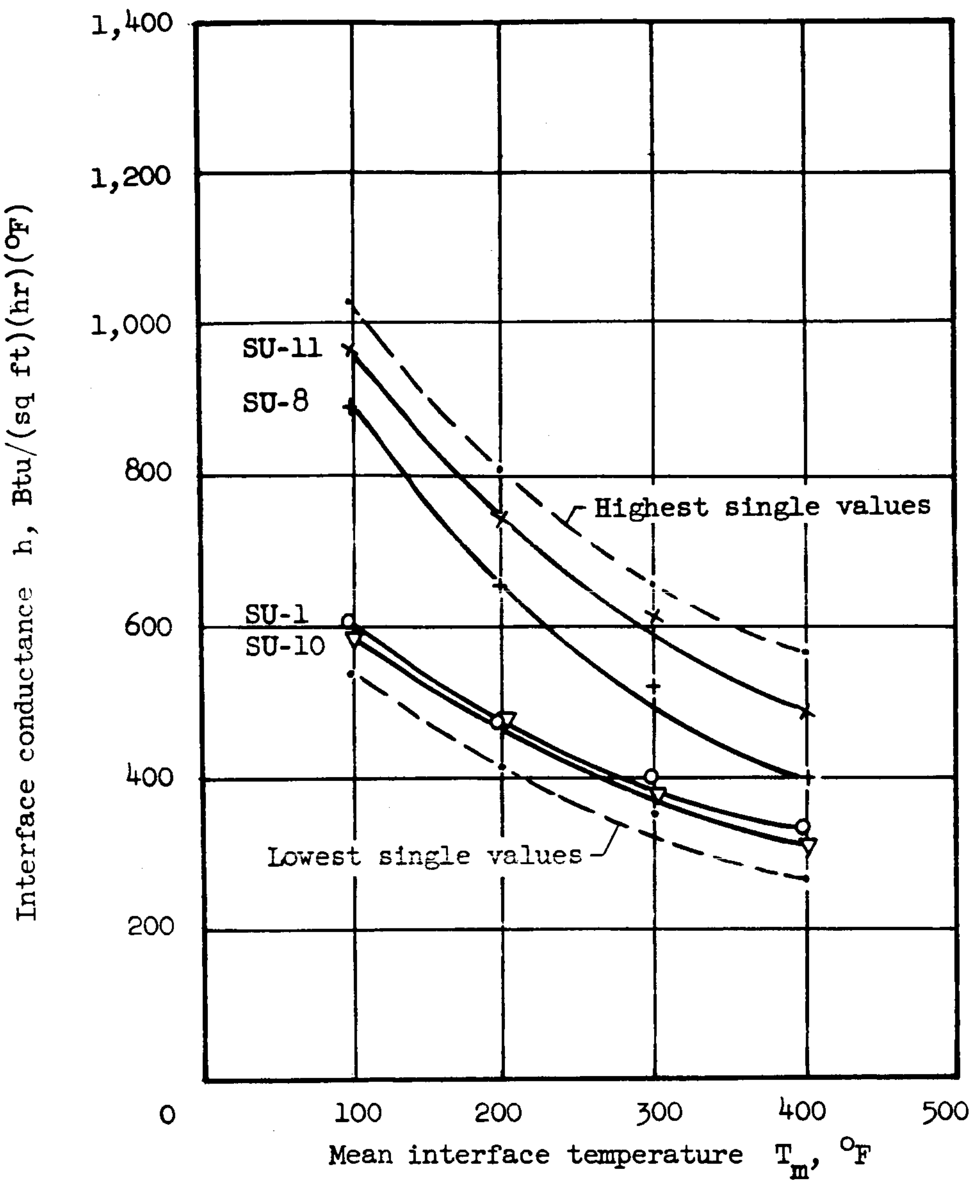

Figure 15.- Comparative interface conductance of four identical specimens (control group) tested at 24-hour intervals (four tests per specimen). Rate of heat flow, 8,000 Btu/(sq ft)(hr).

	Specimen	No. of tests	Rate of heat flow, Btu/(sq ft)(hr)	Test interval
×	SU-2	25	10-12000	24 hr
▽	SU-4	25	8-9000	10 days
+	SU-7	25	7-8000	2-1/2 hr
o	SU-9	25	8-9000	15 min
△	SU-12	3	7-8000	104 days

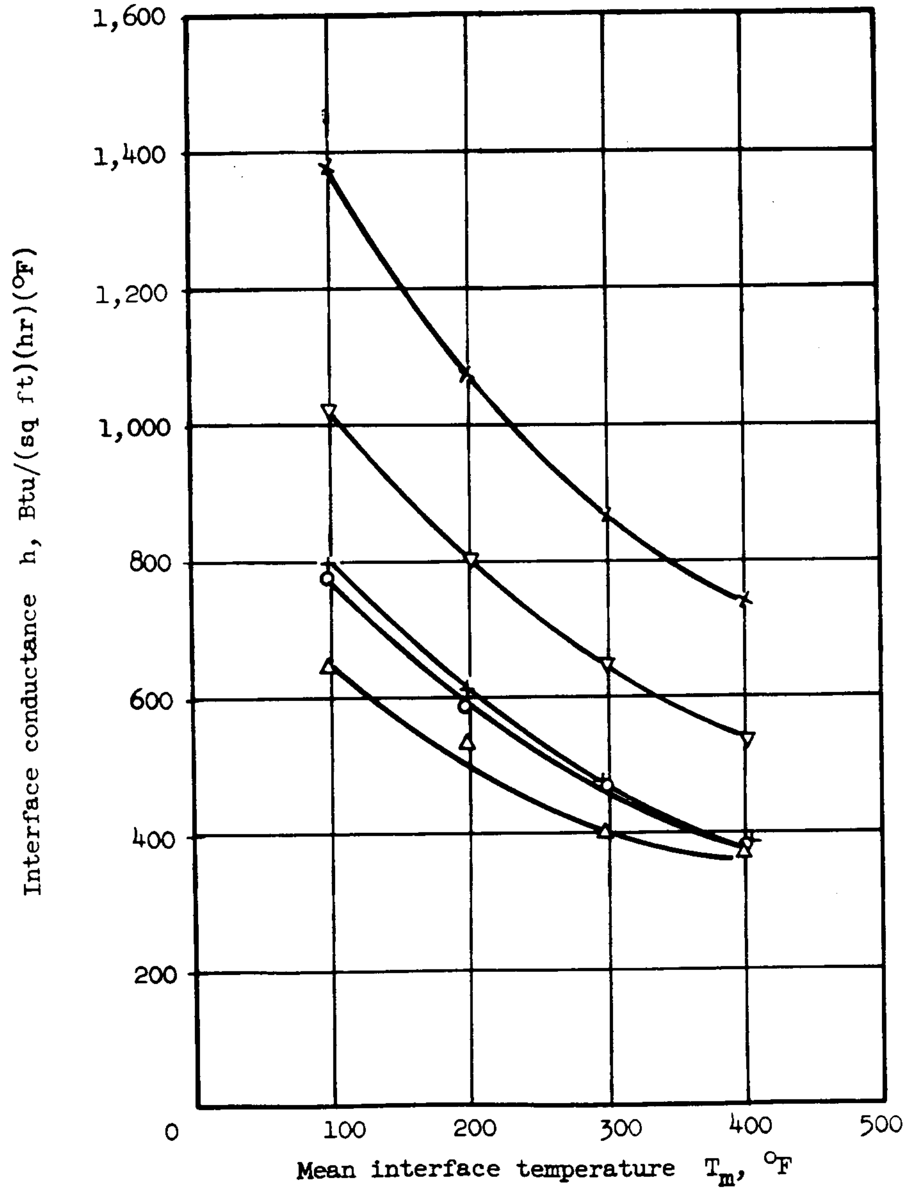

Figure 16.- Comparative interface conductance of five identical specimens tested at various intervals.

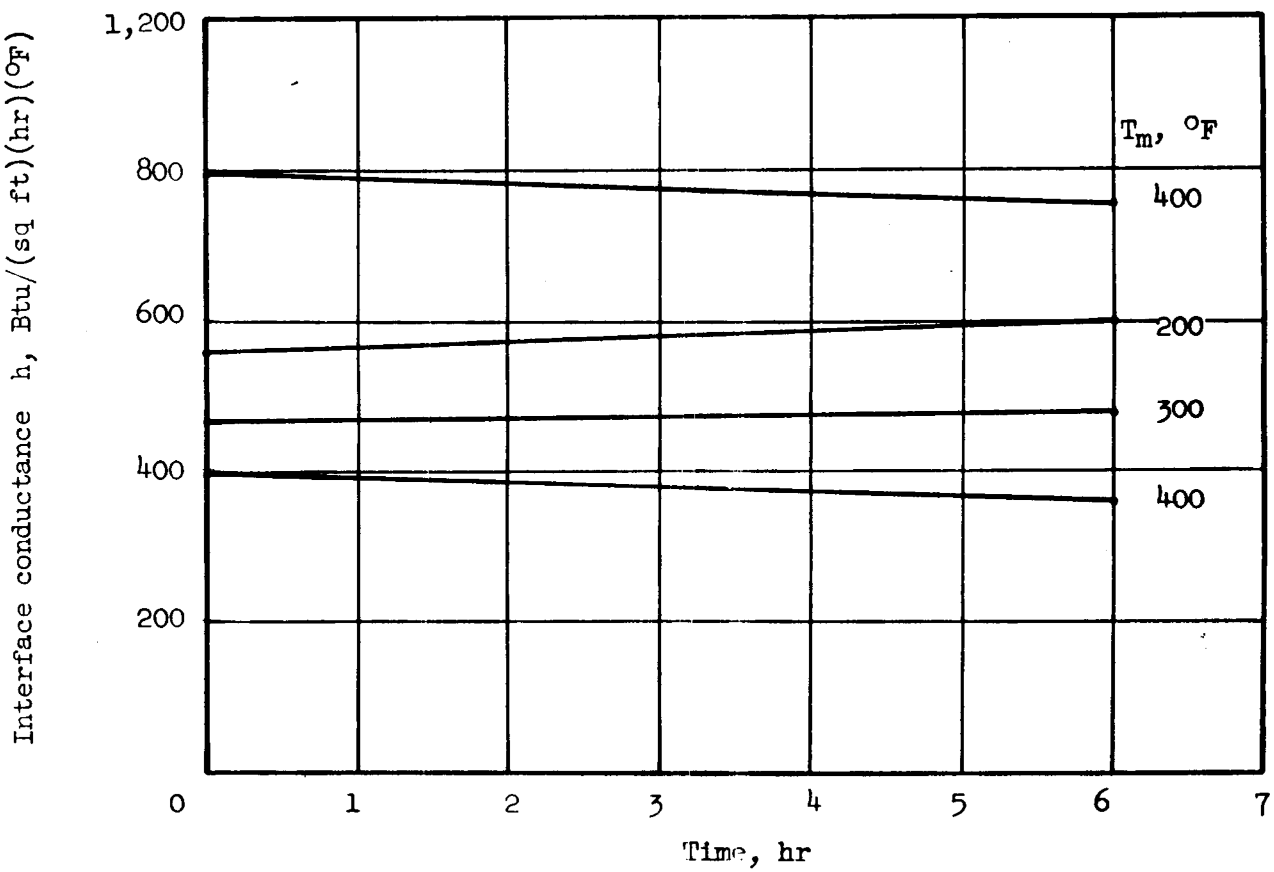

Figure 17.- Statistical trend of interface conductance with elapsed time for specimen SU-9 with 15-minute intervals between tests.